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LIfe Cycle Analysis of an Airlifted Recirculation Aqualculture Facility

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LIFE CYCLE ANALYSIS OF AN AIRLIFTED RECIRCULATION AQUACULTURE FACILITY

A Thesis

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Abstract

Airlift-equipped recirculating aquaculture systems (RAS) provide water-circulation, aeration, and degassing efficiently and reliably. This project investigated the need for biofilters in a fish hatchery environment to address biofouling of tank water from hatching eggs. Eggs of various fish species were selected and Biological Oxygen Demand (BOD), total Kjeldahl nitrogen (TKN), and protein loading and content were measured and compared. Means for all samples were: 0.67±0.05g BOD_5/g, 10.89 nitrogen±0.84% and the mean protein content 69.22±3.82%. A statistical analysis indicates that *Rachycentron canadum* (cobia) and *Ictalurus punctatus* (channel catfish) is the most representative of the multi-species lot when compared to *Balantiocheilus melanopterus* (bala shark), the targeted species for this study. Secondly, this project sought to quantify the costs associated with domestic tilapia growout production using Airlifted PolyGeyser® RAS technology. A cost analysis was applied to a given facility, based on feeding rate and annual production requirements. Results indicated a capital cost of $4,887,000 for the entire facility including $4,671,000 for RAS equipment. The annual production cost of the growout was determined to be $953,140 for the facility. The production cost of growout is $0.93 per pound of fish. The calculated facility equivalent equipment cost was $0.26 and the purge facility $0.1 per pound of fish. The total production cost of the facility per pound of tilapia produced was $1.19. The life cycle costs of the facility over period of 30 years was $25,572,000, of which feeding represents 43% with a cost of $11,056,000. Operation cost has the second highest cost of $5,053,000then stocking cost, of $2,373,000. The thesis presents a tabular template of costs applicable to airlifted PolyGeyser®-equipped facilities.

1. Overview

Recirculating aquaculture systems (RAS) are water-efficient in that they filter and reuse tank water. As they minimize water use, they help save millions of gallons of water each year. Nevertheless, these husbandry systems remain relatively costly (Masser et al., 1999). RAS must also become cost competitive with alternate production modes (ponds, raceways, pens, and cages) to gain popularity among commercial producers. This requires efficient design of its water treatment processes for all stages of husbandry (hatchery, nursery, and growout) (Asian Institute of Technology, 1994; RUFORUM, 2011).

Despite attempts to understand fish oogenesis (egg formation and development) and recent progress on manned production (human-induced) of viable fish eggs, little documentation is available on fish species-specific eggs and larvae (Auld and Schubel, 1978; Wallace and Selman, 1990; Lubzens et al., 2010).

Although biofouling in aquaculture, which can be defined as the process by which accumulation of organic matter stimulate bacterial blooms, is increasingly studied, most publications are concerned with live, grown fish (Guenther et al., 2009; Huntingford et al., 2006). Biofouling in hatcheries results from the presence of dead eggs, egg shell debris, and other organic waste that remains in the tank after hatching. Subsequently, the ammonia level rises making the tank water unsuitable for the remaining fry. There is a need for a filtering system that removes the organic matter in hatcheries. Because the organic waste load differs from species to species, filtering system design must take into consideration the species' loading profile.

The total Kjeldahl nitrogen (TKN) provides a physicochemical characterization of water in terms of nitrogen. TKN level includes both organic nitrogen and ammonia. Thus, TKN level is a reliable indicator of how inhospitable the tank is.

The first part of this thesis addresses the sizing of biofilters in hatcheries. It seeks to develop a species-specific egg biofouling profile. Surrogates for an endangered species' eggs (e.g., bala shark) were used to determine filter loading parameters for TKN and BOD. A statistical analysis established significant similarities in loading among species. This baseline data is needed to determine filter size relation to egg loading.

A PolyGeyser® filter captures and removes solids and dissolved organics as it proceeds to nitrification. Using floating beads, PolyGeyser® units self-wash or self-clean as they recycle their own backwash waters (Malone and Beecher, 2000). Frequent washing assures efficient hydraulic conductivity. They are energy efficient due to a relatively low headloss. The units operate most efficiently with lifts below 12 inches (Gudipati, 2005). The operation is made relatively simple, compared to the other recirculating systems that employ multiple treatment units (Malone and Gudipati, 2005; Malone and Beecher, 2000).

PolyGeysers® are nitrification filters that help reduce fish loss in aquaculture. The beads filter the water, making the system operation relatively simple. The filters are fed by airlifts that inject air into a column to lift and transport the water vertically. By doing so, they degasify (remove the CO_2 from the water) and allow for circulation, and add O_2 water. An Airlifted PolyGeyser® RAS combination performs all these tasks simultaneously: it nitrifies and captures and removes solids and dissolved organics while the airlifts circulate, add oxygen, and strip carbon dioxide. It is cost-effective and its simplicity contrasts with the complexity of most RAS designs (Masser et al., 1999).

The second part of this thesis aims at quantifying the cost associated with large scale tilapia growout production using airlifted PolyGeyser® RAS technology equipped tanks. A cost analysis applicable to PolyGeyser®-equipped tanks is presented as the study provides the financial and

biological rationale for launching a facility. The analysis was performed with feed rate and tank size as the major determinants of production costs.

2. Literature Review

2.1.Ornamental Fish Culture

Ornamental fish are a cash crop in the U.S. and worldwide (Andrews, 1990; Chapman et al., 1997; Steinke et al., 2009). This multi-million dollar industry features the U.S. as one of the major importers, most species coming from Southeast Asia and the Amazon region (Bruckner, 2005; Watson and Shireman, 1996; Halachmi, 2006).

Marine and freshwater ornamental species are increasingly bred and spawn in captivity. The culture of such species is essential to the preservation of endangered species such as the bala shark. In effect, Halachmi (2006) and Tlusty (2002) explain that the development of RAS has allowed for a decrease in the capture of wild ornamental fish species.

Ng and Tan (1997) note that, while too scarcely found in nature, some endangered and ornamental species have been "successfully bred in captivity and conserved." Tlusty (2002) reports that the current legislation favors such a situation. Indeed, as collect on of animals from public bodies of water faces more legal restrictions, aquarium rearing of ornamental species will increase.

Nevertheless, tank aquaculture is also regulated. Southgate (2010) remarks that several external legislative measures and regulations have been put in place to ensure biosecurity for fish tanks, especially regarding the quality of the tank water. However, the author notes that numerous disease-causing agents are ubiquitous in the tank itself.

2.2.Biofouling and Egg Loading

Re-creating the fish's habitat is a complex task. Salvesen and Vadstein (1995) observe that intensive manned incubation differs from the natural process of fish production in regards to the exposure of eggs and larvae to bacteria. While one of the major causes of egg mortality in fish is

genetic deformity (Brown et al., 2010), bacteria transmission from dead eggs to the live larvae increases fry mortality in the hatchery tank.

Ammonia is directly excreted by fish and is produced by decaying fish waste, dead fish, and waste feed. In hatchery tanks, waste is produced both by hatching eggs, and by the decay of dead eggs. In the oogenetic development of fish eggs, ammonium ions accumulate during the late embryonic stages (Finn et al., 1991).

Ip et al. (2001) details the toxic effect of ammonia on fish. Many disagree on whether seawater species are more sensitive to ammonia toxicity than freshwater species[1] (Ball, 1967; Meade, 1985; Arthur et al., 1987; Ruyet et al., 1995; Randall and Tsui, 2002). Nevertheless, ammonia in water has been referred to as "the major toxic nitrogen form in the environment" (Ip et al., 2001). Indeed, this nitrogen form inhibits growth, and causes the gill development disorder hyperplasia (Ip et al., 2001; Smart, 1976; Burrows, 1964). It also hinders energy metabolism needed for embryos to hatch and survive upon hatching. Wright and Fyhn (2001) report that ammonia can damage the developing embryonic tissue.

In the presence of dead, decomposed eggs and debris of hatched eggs, the quality of the water deteriorates and may pose threats to the rest of the living organisms in the tank not only in terms of exposure to nitrogen (ammonia), but can also induce oxygen shortage (Trout Unlimited, 2010). Fish eggs possess an oxygen reservoir within the perivitellin space (below the cell membrane). During the perivitellin space formation, external water penetrates the cell to provide oxygen needed for proper development (Braum, 1973). Oxygen deficiency is the cause of numerous defects in fish. Braum (1973) observed different stages of herring morphogenesis in the

[1] The disparity of results is due to the multiplicity of variables: developmental stage, whether the fish is starved or fed, water temperature, etc.

lower layers of the tank, where there is poor circulation between eggs. Oxygen intake normally increases as the eggs develop, but in the instance of oxygen shortage, eggs suffered morphological retardation, failed to hatch, and those that hatched tended to exhibit small body length. Dead, decaying eggs constitute a build-up of biomass in the tank, which causes a high increase in oxygen consumption, creating a septic environment for the remaining eggs. Wickett's 1954 experiment measured BOD of live salmon eggs in the Nile Creek and determined oxygen demand to be between 0.00013 and 0.0003 mg/egg/hour at a temperature of 0.1° to 8.2°C. Studies such as Steer and Moltschaniwskyj (2007) that evaluated correlation between egg mass, embryo mortality, and biofouling with squid suggest that biofouling is not necessarily lethal for all marine species' eggs.

Removing dead eggs from the hatchery and aquariums is a known need in the domain of aquaculture. Patents have already been submitted as early as the 1870s with the McDonald jar from which eggs were removed with a siphon of rubber tubing (Titcomb, 1910). Models have been modernized mechanically throughout the years.

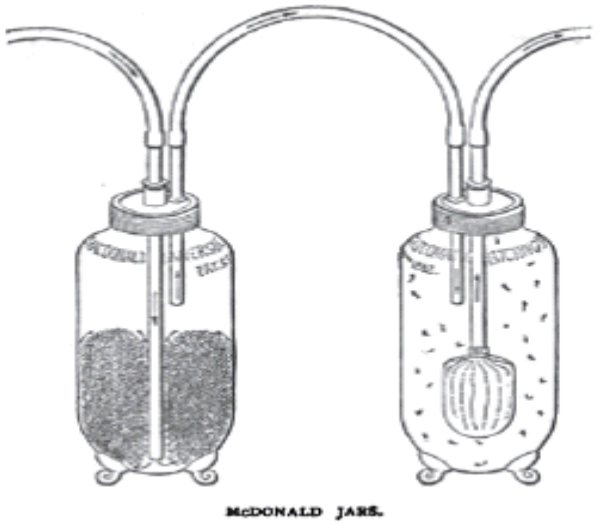

Figure 1: McDonald Jars mechanically remove dead eggs (Source: Mather, 1884)

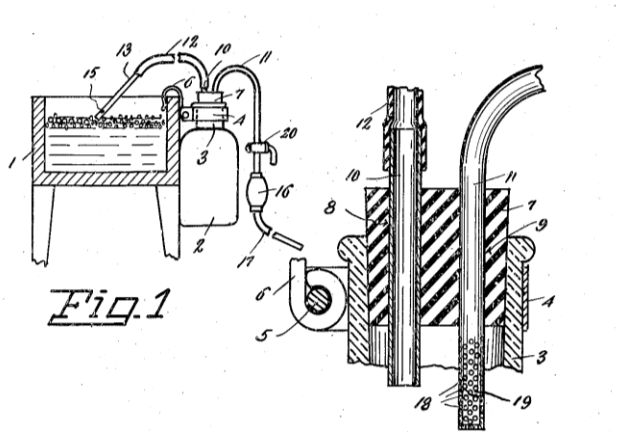

Figure 2: a dead egg removing apparatus (Source: McLeary, 1949)

As an alternative to the mechanical removal of dead fish eggs, Salvesen and Vadstein (1995) evaluated four different chemicals to establish a procedure to disinfect marine fish eggs as an effort to salvage eggs before they die or contaminate the tank. The use of chemicals generates biochemical waste that can be later ingested by fish consumers.

2.3.Contemporary Treatment Options

In 1976, Lewis and Wehr evaluated a closed system – a cage – that uses well water and resembles a biofilter-equipped hatchery pond with the rationale that fish would be "free" when they hatch, yet could undergo "localized disease treatment, localized harvest, and mechanized harvest." The report utilized channel catfish eggs. The cage's pyramid-shaped bottom ends with a suction line that leads to a centrifugal pump. The water then goes down a grassy hill that serves as biofilter, at the bottom of which is a water sump. The sediment is transferred into another tank where it undergoes biofiltering. The sump's nutrient-rich water is mechanically returned to the cage once the waste is removed. The cage's advantage is that it helps decrease BOD and oxygen depletion by removing solid waste from the hatchery. The system's biofilter (the grassy hill) helps retain plant nutrient from the rest of organic waste so that nutrients could be returned to the cage.

The shortcoming of such a device is that although it removes the solid dead eggs, it does not prevent them from fouling the water before they are removed. Inversely, chemical antifoulants such as silicone and copper-based coatings are still being assessed and investigated (Guenther et al., 2009; Braithwaite et al., 2007; Hodson et al., 2000), but such antifoulants do not eliminate the need for mechanical removal of solid dead eggs.

Biological water treatment often involves the use of bacteria, such as *nitrosomonas* species and *nitrobacter* species that oxidize the toxic ammonia into nitrites and then convert nitrites into less toxic nitrates. Such strategy efficiently reduces water toxicity, but after extended loading, the nitrate-rich water still needs to be changed and the tank may need cleaning (Trout Unlimited, 2010).

Fluidized beds, moving bed reactors, and floating bead filters are commonly used for filtration of aquaculture waters (Burden, 1988; Thomasson, 1991; Sandu et al., 2002; Brindle and Stephenson, 1996; Malone and Gudipati, 2005; Malone and Beecher, 2000; Sharrer et al., 2007; Sharrer et al., 2010). Fluidized beds are characterized by a fixed film process that uses hydraulically suspended sand (or plastic) as a biocarrier (Summerfelt, 2006; Weaver, 2006). These filters remove pollutants on large surface areas, enabling oligotrophic water conditions (high quality water required for spawning and larval rearing). However, Weaver (2006) argues that although fluidized beds are adequate for removing soluble components, bead filters are more efficient in removing solid waste. He uses the example of a zebra fish breeding RAS design to show that fluidized beds provide nitrification, and that they are most effective when used in combination with floating bead filters. Less widely used membrane biological reactors are filtering systems that “combine activated sludge type treatment with membrane filtration” (Sharrer et al., 2009). The membrane pores’ size determines organic retention.

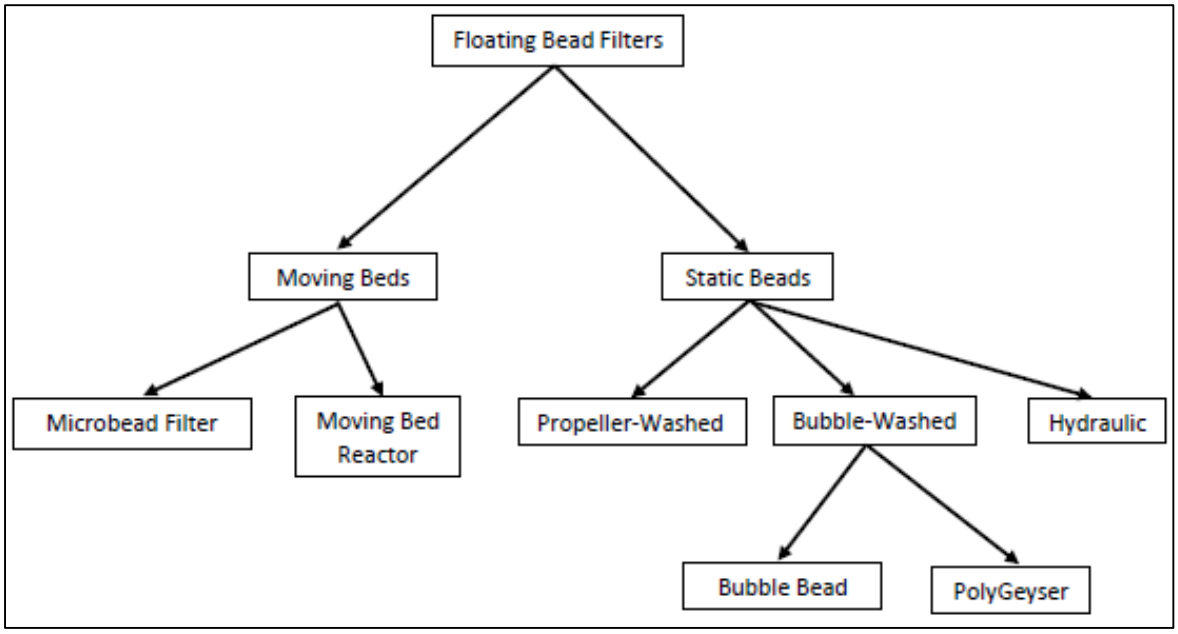

Figure 3: RAS floating bead filters by classification (modified from Malone and Pfeiffer, 2006)

Nevertheless, the separation of liquids and solids often requires a secondary settling tank, which is not only time-consuming, but also limits effluent quality (Hai and Yamamoto, 2011). In municipal wastewater treatment, irreversible membrane damage has also been observed in instances of irregular discharges (Fatone et al., 2007).

Malone and Pfeiffer (2006) present a biofilter classification of floating bead filters (Figure 3). RAS filters with moving media such as the moving bed reactor (Ødegaard et al., 1994; Rusten et al., 2006) or the microbead filter (Timmons and Summerfelt, 1998) feature a mix of water and air that move the filtering media in a constant manner. In RAS filters with static beads, however, the media do not move, as the water goes through the stationary media bed. Static beds such as the propeller-wash filter (Malone and Beecher, 2000; Chitta, 1993), the hydraulic filter (Wimberly, 1990), and the bubble-washed (Sastry et al., 1999) are further divided by their washing technique.

Figure 4: The PolyGeyser® is a pneumatically washed unit that recycles its own backwash waters (Source: Aquaculture Systems Technologies, 2006)

The hourglass or bubble bead are normally manually washed by draining (Johnson, 2008; Hearn, 2009; Malone and Gudipati, 2005). The PolyGeyser® (Figure 4) is designed to automatically backwash.

2.3.1. PolyGeyser® Description

Figure 4 displays the model of a contemporary PolyGeyser®. The concept of this filtering device in the aquaculture arena emerged in the late 1980s from the study of sand's ability to clean and filter water (Malone and Burden, 1988). Dr. Ron Malone submitted a series of patents in the 1990s that specifically addressed the design of floating bead filters (Malone, 1992, 1993, 1995, 1998, 2003). Water flows continuously as a loop through the PolyGeyser® filter at a given flow rate.

A PolyGeyser® bioclarifies water in an RAS. PolyGeyser® units are self-washing or self-cleaning as they recycle their own backwash waters. They can use backwash water repetitively

while retaining their nitrification capacity, which means long life and efficient hydraulic conductivity. They can be energy efficient operating with total headlosses under 12 inches (Malone and Gudipati, 2005).

2.4. Airlifts

The core feature of an airlift is a draft tube partially submerged in water. Air is injected into a draft column. The air/water mixture has a low density and is pushed vertically, upwards (lifted) by a pure water column. The pure water has a higher density and therefore exerts pressure to eject the air/water mixture and replace the air-rich water in the tank.

The work of Gudipati (2005) evaluates the hydraulic performance of airlifts at different flow rates and describes the characteristics of this performance. She evaluated the submergence to lift (S: L) ratio at standard guidelines, and determined 4:1 or 80% to be the ratio at which airlifts are most efficient.

Airlifts remove carbon dioxide (degasification), which is critical for pH control (Loyless and Malone, 1998). Hearn (2009) established capacity/sizing standards with regards to the amount of air needed in marine applications of airlifts. He tested performance characteristics of 20.3 cm diameter airlifts used with warm water marine RAS. He measured that the air injection rate corresponds to 1.3 times that of the liquid flow rate. The 20.3 cm airlift provides up to 3.1 kg oxygen per day, while removing carbon dioxide. Hearn et al., (2009) also evaluated different airlift sizes and produced a correspondence of oxygen and carbon dioxide transfer rates based on different factors: pipe diameter, gas to liquid ratio, and S:L ratio. Johnson (2008) explored the impact of different flow rates on oxygen transport for airlifted wastewater treatment applications.

In aquaculture, airlift use to sustain the rearing the marine species has flourished. Chapman's 1980 patent for a post larval crustacia rearing device contains an airlift that provided

air bubbles to the crustacia (Chapman, 1980). The device imitated the natural air supply in marine waters. Between 1991 and 2001, Lee, Turk, and Whitson introduced a series of patents for automated recirculating filtration systems, which airlift feature proved more cost-efficient than those that feature electric pumps (Lee et al., 2001; Turk and Lee, 1991). The use of airlift pumps is now widespread in the field of aquaculture, as they ensure proper water quality by circulating and aerating water in closed systems that reuse or recirculate their water (Parker and Suttle, 1987; Loyless and Malone, 1998; d'Orbcastel et al., 2009). Airlifts are not as energy-efficient as open aeration systems are regarding the aeration performance, but airlifts have the advantage of providing circulation (Loyless and Malone, 1998; Malone, 2013a). Airlifts limit the need for the additional circulating components in an RAS.

Awari et al. (2004) determine mathematically optimal conditions of airlift pump use and developed a computer program in which users may enter the variables of use conditions to obtain the ideal design parameters for solid-liquid mixtures. Variables include: diameter of raising main, immersion ratio, nozzle diameter, pressure, discharge or flow, head, and % efficiency (Timmons and Summerfelt, 1998).

Wastewater treatment applications of pneumatic washing with the use of bead filters were evaluated by Wagener (2003), Bellelo, (2006), and Johnson (2008). Wagener (2003) evaluated performance of airlift-assisted secondary filtration as applied to wastewater and provides a correspondence of biological (BOD_5) and physical (TSS) treatment based on different variables: hydraulic filtration rate, backwash frequency, and filter configuration. The airlift/SLDM (static low density media – bead bed) was found to produce better BOD_5 and TSS effluent qualities than other secondary wastewater treatments, as it demonstrated higher loading capacities.

2.5. Airlifted PolyGeyser® RAS

Within an airlifted PolyGeyser® RAS, the PolyGeyser® nitrifies and proceeds to solids capture and dissolved organics removal, while the airlifts circulate, add oxygen, and strip carbon dioxide. The airlifts' downstream position allows optimal gas transfer (Malone and Gudipati, 2005). The design approach seeks to achieve cost-effectiveness while overcoming the complex demands imposed on RAS designs (Losordo et al., 1992), by using floating bead bioclarifiers that simplify RAS designs (Malone and Gudipati, 2005; Malone and Beecher, 2000).

Malone and Gudipati (2005) have introduced RAS design criteria based on airlifted PolyGeyser® technology currently employed in the United States in a number of prototype facilities and they provide a list of airlift sizing criteria when used with a PolyGeyser®. In terms of airlift sizing, Hearn (2009) determined 20.3 cm diameter airlifts to be adequate for multiple stages of aquaculture: broodstock, fingerling, and growout.

In an airlifted PolyGeyser® system, airlift capacity must coordinate with the stock grown in terms of density, volume, and feed amount. Alt (2015) studied PolyGeyser® performance as influenced by different loading parameters such as biofilter oxygen, tank total ammonium nitrogen, and carbon dioxide were projected and plotted against daily feed rate.

2.5.1. "Enhanced Nitrification" (EN) Media

Guerdat et al. (2010) stressed the importance of nitrification with PolyGeysers® in reducing fish loss in fish aquaculture. The EN media was a critical element in the evolution of the airlifted PolyGeyser® RAS treatment system. The media displayed extremely low headlosses at flow rates used for high rate nitrification. Low bead bed headlosses, facilitate the airlift operation. Bellelo (2006) considers Static Low Density Media (SLDM) filters used in high-density RAS, but applies different media to the same filter configuration in a domestic wastewater treatment context. He

compared Enhanced Media (EN) and a KMT Kaldnes (KMT) media. As he measured post-primary clarification BOD_5 (carbonaceous biochemical oxygen demand) and TSS (total suspended solids) concentrations, EN was found to reduce 90% both BOD_5 and TSS. The SLDM/KMT combination reduced 10% less. Furthermore, EN was found to generate oxygen uptake twice as high as that of KMT, because of greater surface area per unit volume.

2.6. Cost Analysis

Large-scale tilapia farming is relatively recent in the U.S. Indeed, domestic mass production started about 30 years ago (Josupeit, 2007; Globefish, 2015). Even though the U.S. is still largely dependent on imports, domestic production is increasing, (USDA, 2015). The current increase in RAS use is a turning point in the expansion of the industry (Fitzsimmons, 2000; Molleda et al., 2007).

Watanabe et al. (2002) calculated that the greater financial yield was dependent upon feed expenses and dissolved oxygen (DO) levels, as they noted that low DO killed or stressed fish in ponds. Determining the total cost of fish rearing in a given facility is a complex task. To facilitate cost estimations in RAS, Parker et al. (2012) developed a spreadsheet tool to using tilapia as an example species. The user simply enters the numerical data that applies to his/her own facility (yearly production, number of tanks, etc.) and the pre-recorded formulas adjust costs automatically. Nevertheless, such tool implies that all facilities are uniform, and it allows little room for non-listed equipment or equipment with modified voltage (which would change electricity costs).

Held et al. (2008) analyzed the production parameters and the break-even costs for yellow perch growout. In their study, the fish were hypothetically reared in tanks in a Texas facility. Production parameters were expressed in terms of initial size, stocking density, feeding regime,

weight gain per fish, production in kg per tank, and food conversion ratio. The items considered were related to the facility (land cost, building construction, plumbing, water system, electric service, and labor and maintenance) and the equipment used (tanks, ponds, feeder, labor and maintenance, etc.). Copeland et al. (2005) conducted an economic analysis on the RAS characteristic for black sea bass production. They exposed the complexity of the various parameters involved, such as the impact of the mortality rate on production costs and benefits of RAS use, along with the fluctuation of market prices. Similarly, Beem and Hobbs (1995) stressed the intricate aspect of RAS maintenance costs and their implications, as the least failure to proceed to particularly as poor maintenance can result in rapid, dramatic production loss. The risk of microbial contamination in RAS is also examined by Bowser et al. (1998). Shnel et al. (2002) led a study of discharge and productivity criteria with RAS-reared tilapia. The analysis indicated that RAS require only between 250 and 1,000 L of water per kg of fish and therefore constitutes a source of cost and water reduction in fish production as compared to more traditional culture methods such as ponds (Beem and Hobbs, 1995).

3. Estimating BOD_5 and Nitrogen Loading from Decaying Egg Mass

In hatcheries, loading and biofouling result from egg shell debris, hatching-related fluids, and dead eggs. This organic waste decays in the tank water, leading to oxygen shortage and nitrogen-related fouling that can affect the remaining eggs (Horvath, 1981). In this study, we consider decomposing eggs of bala shark and characterize BOD_5 and nitrogen loading. Results are compared with eggs of 7 other species. The results lay a foundation for design of large-scale commercial breeding system.

3.1. Objectives

The long term objective of this effort was to develop a water treatment approach to resolve the fouling of the water observed in bala shark breeding operations. The specific objectives of this study were:

1. to determine the organic and nitrogen loading using eggs from abundant species
2. to determine which species produces eggs with similar waste loading characteristics to the bala shark (*Balantiocheilos melanopterus*)
3. to establish the baseline waste loading expectations for a typical breeding operation laying the foundation for a hatchery filtration system across species.

3.2. Background

Balantiocheilos melanopterus, commonly known as the bala shark (also called silver shark, tricolor shark, or shark minnow) has an average adult length of 54 cm. Young fish are a favored ornamental species and has been overexploited. Padmakumar et al. (2014) and Ng and Tan (1997) describe this particular species as endangered. Early attempts to breed bala sharks in the U.S. were complicated by high mortalities in the hatching stage (Ng and Tan, 1997). These procedures involved the maturation of pond raised fish. The eggs were placed in tanks, hatched, and varied

for about one week before introduction to grow out ponds. High mortalities were attributed to poor water quality conditions in the hatching tanks. Observations indicate that tank water used in the bala shark breeding fouls when eggs die, jeopardizing the hatch.

While Southgate (2010) noted that numerous disease-causing agents and bacteria were ubiquitous in the tank itself, Salvesen and Vadstein (1995) indicated that intensive manned incubation exposed eggs and larvae to certain bacteria that they would not encounter in the natural process. Industrial fish reproduction tends to promote fish diseases and bacteria transmission from fish eggs to the live larvae and fish in the hatchery tank. The presence of dying and dead eggs in the hatchery tank is a problem in that it creates a domino effect that hinders the healthy development of all other live eggs, and fry. Brown et al. (2010) compared data on wild and captive fish and concluded that the high rate of deformity among fish was a symptomatic response to aquaculture-imposed conditions of hatchery-reared fish: "robust fingerling production remains a serious impediment to the cultivation of numerous technically difficult species with otherwise good aquaculture potential." In addition, Brown et al. (2010) explained that the high rate of egg mortality is mostly due to genetic deformities, and added that such a phenomenon is a typical and growing problem of aquarium-reared ornamental fish where the gene pool was more limited.

The presence of disease-causing agents, as well as nitrifying bacteria (Madsen and Dalsgaard, 1999; Oh et al., 2002; Malone and Pfeiffer, 2006), and salinity can also affect mortality rates (Johnson and Katavic, 1984; Shinn et al., 2013).

Exposure to nitrogen (ammonia) and inappropriate dissolved gas concentrations (oxygen shortage, for instance), due to the presence of dead eggs, seems to be the greatest hazard to egg survival. In hatchery tanks more specifically, waste is produced not only by hatching eggs, but also by dead eggs that remain in the tank. Finn et al. (1991) explained that in the oogenetic development of fish

eggs, ammonium ions accumulated during the late embryonic stages. The authors also suggested that hatching eggs added more ammonia that was lethal for the remaining, unhatched eggs. In addition, dead eggs that do not hatch and are not removed decompose and worsen the ammonia problem (Trout Unlimited, 2010).

Ip et al. (2001) detailed the toxic effect of ammonia on fish. Ammonia inhibits growth, and for fish, causes the gill development disorder hyperplasia (Ip et al., 2001; Smart, 1976; Burrows, 1964). It also hinders energy metabolism needed for embryos to hatch and survive upon hatching. Wright and Fyhn (2001) more precisely reported that ammonia could damage the developing embryonic tissue.

Ammonia nitrogen loading measurements are used as part of the physicochemical characterization of water, and experts agree that a high level of nitrogen-derived ammonia is a steady indicator of water toxicity (Trout Unlimited, 2010). Therefore tests such as total Kjeldahl nitrogen (TKN) help determine water quality. For instance, high levels indicate not only protein contamination (Vaithanomsat and Kitpreechavanich, 2008), but also potential biofouling. Nitrogen loading is a source of great contamination for live fish (Bergheim et al., 1984; Handy and Poxton, 1993; Shinn et al., 2013). Although the direct effect of nitrogen loading on fish eggs still needs to be further researched, it is reasonable to assume that its potentially lethal effect it has on hatched fish is comparable or somehow proportional on fish eggs as well (Szluha, 1974). Concentrations of nitrogen and protein in organic samples are related (Tomé and Bos, 2000). Indeed, protein amounts and protein synthesis are controlled to a large extent by nitrogen and amino acid concentrations (Tessari, 2006).

Although biofouling may not be directly lethal for marine species' eggs (Steer and Moltschaniwskyj, 2007), Hattori et al. (2004) studied the effect of varying amounts of dissolved

oxygen in the rearing tank. Oxygen deficiency was analyzed on a pathological viewpoint as the cause of numerous defects in fish. In the case of fish eggs, dead, decaying eggs constitute a build-up of biomass in the tank, which causes a high increase in oxygen consumption, and therefore creates a septic environment for the remaining eggs (Lovegrove, 1979; Cronin et al., 1999). Biochemical oxygen demand (BOD) corresponds to the oxygen amount aerobic organisms need in order to break down (consume and digest) organic matter. BOD is controlled by protein levels and, to a greater extent, the concentration of sugar and starch that enable metabolism (Church et al., 1977; Cook et al., 2003; Wells and Wendorff, 2004). Thus, biofouled water contains more organic matter (carbohydrates) that constitutes available energy for organisms. Wickett's 1954 experiments measured BOD of live salmon eggs in the Nile Creek and determined oxygen demand to be between 0.00013 and 0.0003 mg/egg/hour at a temperature of 0.1° to 8.2°C. Lowering oxygen content or lack of water circulation was found to result in higher egg mortality.

In the case of hatchery engineering, re-creating the fish's habitat is all the more complex given that eggs and mature fish do not necessarily live in the same trophic level (Malone and Pfeiffer, 2006). Malone et al. (1990) conducted a waste characterization study where they collected water quality data regarding the aquatic environment of another endangered species, the Kemp's Ridley sea turtle. Water was tested for ammonia, nitrogen excretion, and BOD. The information collected served as preliminary data in the design of a recirculating holding system for Kemp's Ridley sea turtles (Malone et al., 1990).

Malone and Pfeiffer (2006) illustrated the preliminary ratings needed in order to determine biofilter sizing. They categorized filters and filter performance to match RAS applications based on total ammonia nitrogen (TAN) loading and provide biofilter classifications based on trophic levels from ultra-oligotrophic for larval production to hypereutrophic and acidic hypereutrophic.

Oligotrophic production systems are characterized by a severely limited amount of nutrients (Malone and Pfeiffer, 2006). These systems are ideal for hatchery tanks because of the low degree of nitrogen and organic waste which degradation leads to oxygen consumption – and/or pollutants – at the eggs' expense (Ip et al., 2001; Smart, 1976; Burrows, 1964; Wright and Fyhn, 2001; Lovegrove, 1979; Cronin et al., 1999). The oligotrophic standard for biosecure fry production is under 0.3 g N/m^{-3} (Malone and Pfeiffer, 2006; Weaver, 2006). Controlled maturation studies indicate that some species' eggs require an even lower (ultra-oligotrophic) TAN level <0.1 g N/m^{-3} (Watanabe et al., 1998; Malone et al., 2006).

Comparative studies suggested that fish species have comparable habitats, or habitats that could be manipulated into similar environments for research purposes (Armstrong et al., 2003). Smith and Noll (2009) explained that "except for temperature, salinity, and dissolved oxygen, there are relatively few differences between species for the other water qualities." Nevertheless, Eding et al. (2006) expressed the need for species-specific filters, as opposed to Malone and Pfeiffer (2006) that cited the need for unitarity in trophic level.

In RAS filters under oligotrophic conditions, biofilms are considerably thin and heterogeneous (Malone and Pfeiffer, 2006). Diffusion to nitrifiers is relatively easy and nitrification rates are moderate despite low TAN levels. Bacterial counts are relatively low as well (Michaud et al., 2006). However, the oligotrophic water conditions are altered in the presence of dead eggs, which inevitably affect the rest of the tank, especially larval fish which are extremely sensitive to trophic water quality changes (Brown et al., 2010). As the eggs decay, there is an increase in both carbon and nitrogen levels. The tank's biofilms therefore thicken, and diffusion into the biofilms subsequently slows. In terms of biofiltering capacity, increased nitrogen loading pushes these oligotrophic RAS systems (designed for low loading) toward a mesotrophic or even

eutrophic condition, thereby making the filter sizing inadequate for the filtering needs of the eggs and fry as the bacterial count rises (Malone and Pfeiffer, 2006).

More recently, Fahandezhsadi (2014) tested larval production systems with high TAN for freshwater ornamental fish. She explored the conversion of TAN into removable microbial biomass via heterotrophic bacteria/plastic system combination (bioplastic biofilter). These heterotrophic filters were capable of operating as bioclarifiers in basic and acidic (pH 8 and 6.5) ornamental fish hatchery water. No traditional dissimulatory nitrification was required.

3.3. Methods

3.3.1. Overview

Eggs of seven different species were selected for comparison to bala shark eggs. BOD, nitrogen, and protein content were determined for each. These selected species are more abundant, more easily and readily available, and cheaper than bala shark. Table 1 lists the species selected, along with their aquatic habitat.

3.3.2. Egg Collection

All egg samples were outsourced in summer 2012 for the study. Eggs of potential surrogate species (blackfin tuna, cobia, snapper, speckled trout, and yellow fin tuna) were collected from CoCo Marine in New Orleans, Louisiana, with the help of Dr. Ed Chesney from Louisiana Universities Marine Consortium (LUMCON). In addition, Dr. John Hargreaves from Aquaculture Assessments, LLC. in New Orleans provided catfish and tilapia eggs. Bala shark eggs were produced at and provided by the Institute of Food and Agriculture Sciences of the University of Florida Cooperative Extension Service, with the assistance of Craig Watson.

Table 1: Nine marine and freshwater fish species of eggs were sampled for the study.

Scientific Name	Common Name	Water Type
Balantiocheilus melanopterus	Bala Shark	Freshwater
Cynoscion nebulosus	Speckled trout	Marine
Ictalurus punctatus	Catfish	Freshwater
Lutjanus campechanus	Snapper	Marine
Oreochromis niloticus	Tilapia	Freshwater
Rachycentron canadum	Cobia	Marine
Thunnus albacares	Yellowfin tuna	Marine
Thunnus atlanticus	Blackfin tuna	Marine

3.3.3. Solidifying the Samples

All eggs were freeze-dried in a Labconco LYPH-Lock 18 freeze-dryer and placed in a Whirlpool® upright freezer to preserve the organic composition while removing the handling limitations related to moisture. Freeze-dried samples were powdered via a Hamilton Beach® coffee grinder. Powdering dry eggs increases the surface area of the particles and facilitates the manipulation and measurement of each sample. The increased surface area facilitates the degradation in the BOD_5 test, thereby providing a worst case scenario for O_2 consumption. Powder form improved accuracy in weight measurements. Figure 5 shows the powder form of eggs from different species.

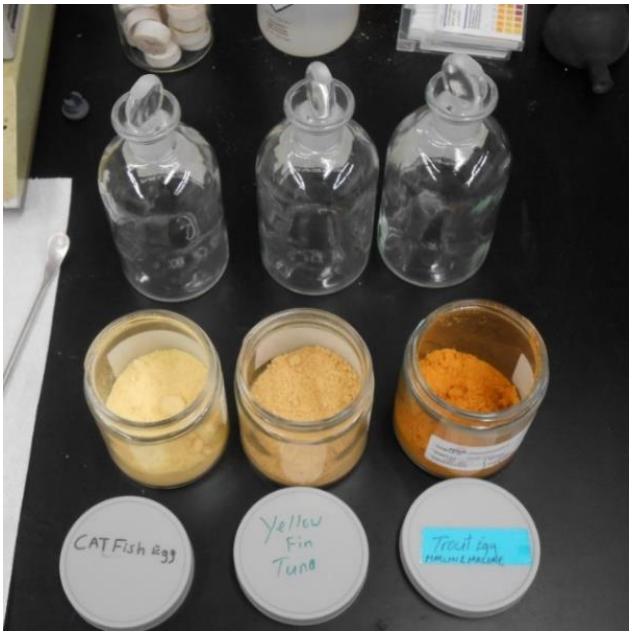

Figure 5: Freeze-dried egg samples were placed in sterile jars, then added to distilled water in the BOD bottles.

3.3.4. Loading Measurements

The O_2 probe (Accumet XL40 Benchtop Dissolved Oxygen Meter) was calibrated using the Winkler method (McCormick, 1972) as protocol to determine the dissolved oxygen. The Winkler method was selected for its accuracy (Carpenter, 1965a; Peck and Uglow, 1990; Helm et al., 2009). A calibration curve of the BOD_5 probe was created with 5 calibration data points. A fixed weight of freeze-dried eggs was measured (1.5 mg) and added to the BOD bottles.

To prepare and stock the egg solution, distilled water was aerated at room temperature. The volume for each sample of stock solution was set at 300 mL dilution water. The initial and final (5 day) O_2 were measured with the meter in mg/L, enabling the calclulation of how much O_2 was consumed. All measurements were triplicated. The BOD_5 in gram per gram of sample was then calculated (American Public Health Association, 1976).

For TKN measurements, 1.025 g of dry weight power was measured in triplicate for each species' egg sample into a foil paper. Samples were inserted into a nitrogen analyzer (LECO FP 528) that analyzes organic samples and gives a reading of % nitrogen. Samples of the same weight (1.025 g) were analyzed for % protein in a LECO FP 528 as well.

3.3.5. Statistical analysis

The data acquired from the aforementioned measurements was input in SAS and an ANOVA was conducted. A Tukey Studentized test identified similarities by grouping, based on mean value.

3.4.Results

Table 2 displays averaged BOD_5 results as well as nitrogen and protein content for each species tested. BOD_5 results range from 0.622 g/g to 0.750 g/g. Nitrogen levels range between 9.2403% to 11.701%, and protein levels between 61.411% and 73.169%. Results were consistent across the board for all trials of the triplicated tests.

Table 2: Levels from BOD_5, nitrogen, and protein for the eggs of all 8 species tested

Scientific Name	Common Name	BOD_5 (g/g)	Nitrogen %	Protein %
Balantiocheilus melanopterus	Bala shark	0.64±0.00	10.97± 0.06	68.55± 0.36
Thunnus atlanticus	Black fin tuna	0.62±0.01	11.67± 0.12	72.84± 0.60
Ictalurus punctatus	Catfish	0.66±0.01	10.92± 0.09	68.30± 0.28
Rachycentron canadum	Cobia	0.64±0.01	10.83± 0.06	67.74± 0.22
Lutjanus campechanus	Snapper	0.71±0.02	9.24± 0.15	61.41± 0.92
Cynoscion nebulosus	Speckled trout	0.71±0.01	10.13± 0.29	68.40± 0.55
Oreochromis niloticus	Tilapia	0.75±0.01	11.67± 0.31	73.10± 0.42
Thunnus albacares	Yellow fin tuna	0.63±0.01	11.70± 0.00	73.17± 0.04

The BOD_5 results for the Tukey's Studentized Range Test in Table 3 showed the mean in g/g of the triplicate results. Identical Tukey grouping letters indicated the mean BOD_5 results were not significantly different. Likewise, the box plot shows the distribution the BOD_5 and the grid location of each species. Based on Table 3 and Appendix A, tilapia eggs had the highest mean out of all species, with a BOD_5 of 0.750±0.011 g/g and the Tukey grouping letter 'A.' Catfish, cobia and bala shark eggs showed no significant difference with means at 0.663±0.011 g/g, 0.644±0.012 g/g, and 0.637±0.004 g/g, respectfully. They were all characterized by the Tukey grouping letter 'C.' Bala shark also showed no significant difference with black fin and yellow fin tuna which BOD_5 (g/g) mean was 0.622±0.008 g/g and 0.630±0.006 g/g, respectfully. They shared the Tukey grouping letter 'D.' Snapper and speckled trout eggs had the second and third highest BOD (g/g) of 0.715±0.016 and 0.714±0.009, respectively. They shared the Tukey grouping letter 'B.'

Table 3: Mean BOD Tukey's Studentized Range (HSD) test for 8 species tested shows 4 different groups (A-D)[2].

Tukey Grouping		Mean(g/g)	N	Species
A	A	0.750	3	Tilapia
B	B	0.715	3	Snapper
B	B	0.714	3	Speckled trout
C	C	0.663	3	Catfish
C	D	0.644	3	Cobia
C	D	0.637	3	Bala shark
	D	0.630	3	Yellowfin tuna
	D	0.622	3	Blackfin tuna

[2] Means with the same letter are not significantly different.

The next variable that was tested in triplicate and analyzed was nitrogen content. Table 4 and Appendix A's box plot show the mean nitrogen in g/g. Identical Tukey grouping letters indicated the mean nitrogen of each species' eggs that were not significantly different. The box plot likewise shows the nitrogen distribution and the grid location of each species. The result indicated that black fin tuna, tilapia and yellow fin tuna had the highest means, with nitrogen loading (g/g) of 0.117± 0.115, 0.117± 0.314 and 0.117± 0.001, respectfully, and a Tukey grouping letter of 'A.' Bala shark, catfish and cobia showed no significant difference with mean nitrogen loading (g/g) of 0.110± 0.058, 0.109± 0.085 and 0.109± 0.058, respectfully, and a Tukey grouping letter of 'B.' Speckle trout and snapper eggs showed the lowest mean of nitrogen (g/g) of 0.102± 0.295 and 0.093± 0.151, respectively Tukey grouping letters 'C' and 'D'.

Table 4: Nitrogen Tukey's Studentized Range (HSD) test for 8 species tested shows 4 different groups (A-D)[3].

Tukey Grouping	Mean (%)	N	Species
A	11.700	3	Yellowfin tuna
A	11.670	3	Tilapia
A	11.667	3	Blackfin tuna
B	10.967	3	Bala shark
B	10.921	3	Catfish
B	10.833	3	Cobia
C	10.131	3	Speckled trout
D	9.241	3	Snapper

[3] Means with the same letter are not significantly different.

Table 5: Protein Tukey's Studentized Range (HSD) test for 8 species tested shows 3 different groups (A-C)[4]

Tukey Grouping	Mean (%)	N	Species
A	73.310	3	Tilapia
A	73.170	3	Yellowfin tuna
A	72.838	3	Blackfin tuna
B	68.550	3	Bala shark
B	68.403	3	Speckled trout
B	68.320	3	Catfish
B	67.742	3	Cobia
C	61.401	3	Snapper

The final variable that was tested and analyzed is mean percent protein for all 8 species of fish egg in triplicates. Table 5 and Appendix A's box plot show the mean percent protein in g/g. Again, identical Tukey grouping letters indicated the mean percent protein of each species' eggs that were not significantly different. The result indicated that tilapia, yellow fin and black fin tuna eggs had the highest mean percent protein of all species with 73.10± 0.42, 73.17± 0.041 and 72.84± 0.60, respectfully, and a Tukey grouping letter of 'A.' Bala shark, speckle trout, catfish and cobia eggs showed no significant difference with mean percent protein of 68.549 ± 0.362, 68.40± 0.55, 68.30± 0.28, and 67.74± 0.22, respectively, and a Tukey grouping letter of 'B.' Snapper eggs showed the lowest mean percent protein of 61.41± 0.92 with a Tukey grouping letter of 'C.'

3.5.Discussion and Conclusion

Results show a similar trend between nitrogen and protein concentrations, but a difference between this trend and that of BOD_5, as seen in Table 2. Bala shark, cobia, and catfish emerge as the species with no statistical difference in all dependable variables test categories (BOD_5,

[4] Means with the same letter are not significantly different.

nitrogen, and protein). The ANOVA test shows that all three species display similar dead egg loading. Since the bala shark is an endangered species, research on biofiltering for bala shark hatcheries can be conducted with either cobia or catfish eggs. A synthesis of the ANOVA results are displayed in Table 6.

Table 6: Catfish and cobia displayed no significant differences from bala shark eggs for each test

Test	Species with no significant differences from bala shark
BOD_5	blackfin tuna, **cobia, catfish**, yellowfin tuna
Nitrogen	**cobia, catfish**
Protein	speckled trout, **cobia, catfish**

Species listed in bold can be selected as surrogates for the bala shark. Using eggs of more abundant species and finding statistically significant similarity with bala shark eggs will help make experimental research and trials more feasible financially. Naturally, catfish and bala shark are both freshwater species, while cobia which is the statistically similar to the bala shark is a marine species. Yet, we recommend cobia over catfish because of its strongest similarity in terms of numerical results. The experiment shows that natural habitat differences do not constitute a limitation when utilizing surrogates. Similarity could also be attributed to the cobia's adaptive abilities. Indeed, this fish has recently been bred and farmed in freshwater successfully (Liao et al., 2004; TheFishSite News Desk, 2007).

Now that biofouling has been assessed in terms of organic and nitrogen loading, the next step is to build an adequate filter to reduce biofouling accordingly. Next steps should include substituting bala shark eggs with catfish or cobia eggs in the evaluations of filtering devices, as well as utilizing data to develop design guidelines for ornamental breeding application.

4. Cost Analysis

Despite growth in domestic production, over 70% tilapia consumed in the U.S. is imported (Globefish, 2015), most of which directly from China. Commercial-scale domestic production can be expanded with the use of RAS. Quantifying the costs and benefits of commercial aquaculture production using RAS requires a detailed economic analysis.

RAS technologies are increasingly used for tilapia production. Indeed, a hardy species, tilapia is adaptive to different water environments. It can withstand the presence of bacteria and survive in adverse water conditions. It is tolerant to elevated TAN and nitrite concentrations (Malone and Pfeiffer, 2006). In this chapter, we perform a cost analysis of growout tilapia production on a hypothetical facility that uses airlifted PolyGeyser® RAS technology. We determine capital costs that constitute the original investment, as well as operation costs that reflect the financial impact of production-related variables.

4.1. Objectives

This chapter provides a framework for economic assessment in airlifted PolyGeyser® RAS, focusing on the growout stage application of RAS. The objectives include: a) The assessment of the direct normalized cost for Nile tilapia growout production (in dollars per lb.) for a commercial scale airlifted PolyGeyser® RAS facility located in the southern part of the United States; b) The mathematical determination of the influence of loan interest rate on the facility's financial (present, annual, and future) worth.

4.2. Background

Aquaculture is already known to be more beneficial than cattle and poultry production in terms of nutritional and production time benefits (Helfrich and Garling, 2009). Tilapia is an alternative to meat and other, more expensive fish species because of its suitability for intensive a

culture. It is tolerant to various environmental conditions (including poor water quality and saline water) (El-Sayed, 2006). The development of U.S. intensive tilapia farming is a contemporary phenomenon (Josupeit, 2007; FAO, 2011). North American production is on the rise, but most tilapia consumed in the U.S. is still produced abroad, mostly in Asia and Central America (USDA, 2015). Fitzsimmons (2000) and Watanabe et al. (2002) noted that the U.S. fish production industry was a leader in the development and engineering of recirculating techniques. RAS thus constitute a new investment in modern-day U.S. aquaculture, as their use has become more widespread throughout the past 30 years (Molleda et al., 2007), and are a key contributor in the expansion of the industry.

Otoshi et al. (2003) compared shrimp growth in RAS and in ponds. Growth to growout size was slightly lower in RAS, which could be attributable to the lack of natural productivity. Otherwise, there were no noted drawbacks (survival, reproductive performance, or productivity rates). The water quality was better in RAS, and RAS also offered a more controlled environment in terms of temperature and ventilation. Nevertheless, due to more rapid growth, ponds provided faster pay back. The study also showed that RAS offer biosecurity, whereas the presence of any infection agent could jeopardize the survival of an entire harvest in other production systems. While Otoshi et al. (2003) provided experimental results; Moss and Leung (2006) studied the economics of pond v. RAS shrimp production. They explained that RAS shrimp production was significantly cheaper ($4.38/kg v. $6.71/kg), reflecting multiple harvests and biosecurity.

Helfrich and Libey (1991) who had predicted that tilapia could be the cash crop of the 21st century also compared production management and costs in different systems. RAS provided a more controlled environment as opposed to ponds where the fish was more exposed and vulnerable to environmental changes. This controlled environment allows for year-long production and

multiple harvests, and therefore increases profit (Helfrich and Libey, 1991). Furthermore, with less water usage, RAS are more appropriate for intensive production. Overall better flavor is noted with RAS-produced tilapia, because ponds contain contaminants detectable in fish taste. In addition, RAS require less space, which reduces land costs. However, RAS have a higher initial capital cost. They require more skilled labor, which increases operation costs. Moreover, RAS are more dependent on mechanical and electric power, thus a power outage can compromise the entire production.

Malone and Gudipati (2005) introduced RAS design criteria based upon an airlifted PolyGeyser® technology that is currently being employed in the United States in a number of prototype facilities. The design approach seeks to achieve cost-effectiveness while overcoming the complex demands imposed on RAS designs (Masser et al., 1999). Malone (2013b) discussed design modifications needed when applying empirical laboratory data to actual commercial scale tilapia production facilities. Commercial practice demonstrated that an increase in airlift sizing criterion (from 1 ft/sec to 1.5 ft/sec) for airlifts with diameters ≥ 6 in. was possible. Cost considerations (the high price of reducer fittings) led to a reduction of the approach pipes' design velocities (from 2-3 ft/sec to 1.5 ft/sec criterion). The PolyGeyser® sizing criterion was unchanged (1.5 lbs feed/ft³/day), but it is observed that the large scale PolyGeysers® not reach their maximum capacity in early facilities. This was due to limitations imposed by, among other secondary factors, water volume (>200 gal. /lb. feed/day) or blower capacity (> 4 cfm/lb. feed/day). The study recommended "continued refinement in design criterion."

Malison and Held (2006) and Held et al. (2008) analyzed the production parameters and the break-even costs for yellow perch growout in farm ponds and in RAS, respectively. Production parameters were expressed in terms of initial size, stocking density, feeding regime, weight gain

per fish, production in kg per tank, and food conversion ratio. They included an analysis of investment costs. The items considered were related to the facility (land cost, building construction, plumbing, water system, electric service, and labor and maintenance) and the equipment used (tanks, ponds, feeder, labor and maintenance, etc.). The authors also included an editable spreadsheet. For RAS production, profitability started at $3.30/lb., but the break-even cost decreased with time, based on the number of cycles input in the spreadsheet.

Copeland et al., (2005) conducted an economic analysis on the RAS characteristic for black sea bass production. They examined the complexity of the various parameters involved, including the impact of the mortality rate on production costs and benefits of RAS use, along with the fluctuation of market prices. Similarly, Beem and Hobbs (1995) stress the intricate aspect of RAS maintenance costs and their implications, as even a small failure to follow maintenance procedures can result in rapid, dramatic production loss. The risk of microbial contamination in RAS was examined by Bowserg et al. (1998).

Helfrich and Libey (1991) conducted a comparative analysis of RAS, ponds, and raceways. RAS were viewed favorably for their ability to rear fish at higher densities, for their controllable environment, and high water reuse. New water is used only to compensate for evaporation and sludge removal. The study of Molleda et al. (2007) compared water quality and consumption in RAS with that in Limited Reuse Systems (LRS) for a culture of Arctic charr. Results indicate a better water quality with LRS but greater water consumption, which resulted in higher costs. Losordo and Westerman (1994) used STELLA modelling language to complete a computerized simulation of small-scale RAS tilapia production featuring a floating bead filter with a rotating biological contactor used in series. Dissolved oxygen was added externally. The simulated facility included both fingerling and growout systems. Their simulation indicates a production cost of

$1.27/lb. Based on their model sensitivity analysis, "improvements in the performance efficiency of system components [do] not greatly affect fish production cost." However, variables that can significantly reduce cost are feed cost reduction, feed conversion ratio improvement. Greater gains are also dependent upon production capacity and decreased investment costs.

The relative cost of recirculation pertaining to the alternative systems (ponds and net pens) can be expected to decrease, even though baseline costs will continue to increase (Malone and Gudipati, 2005). Malone (2013a) noted that raceway tanks can be costly, and he contrasted axial flow pumps that have a low operation cost but a high initial capital cost, with airlift pumps that are inexpensive and considerably energy efficient. In light of such decrease in cost, Malone and Gudipati (2005) predict an increased use of recirculating systems use as well as a diversification of their uses into growout use. Although bead media have been criticized for being relatively expensive to produce (Gutierrez-Wing et al., 2007; Castilho et al., 2009), investment costs for bead filter-equipped RAS are also expected to decrease (Chanprateep 2010, Fahandezhsadi, 2014). Parker et al. (2012) developed a spreadsheet tool to facilitate cost estimations in RAS using tilapia as an example species. Helfrich and Garling (1985) noted that when determining the cost of aquaculture production, the planning stage is quite complex because numerous biological, economic, and legal factors must be taken into consideration. They explained that preliminary research on feasibility constitutes the first step to take to ensure the success of any commercial aquaculture project. To determine the total production cost, one must also consider additional parameters related to capital investment costs, such as: equipment cost (tanks, pipes, etc.), material cost or items that help sustain the process (e.g., fish, eggs, feeding, etc.), installation cost, working capital, project engineering, and management (rate charged by fishery engineers, researchers, lawyers, and other consultants).

4.3.Proposed Facility

The proposed facility is a set of buildings assumed to be already equipped with a water source (water well). The farm campus is made up of polyethylene greenhouses[5]. The greenhouse design presented in Figure 6 is similar for all 6 buildings. It is adapted from the Sumner (2000)[6], and greenhouse heating requirements are obtained from a template developed by Jones (2010). Figure 7 is a blueprint of the spatial arrangement of the facility.

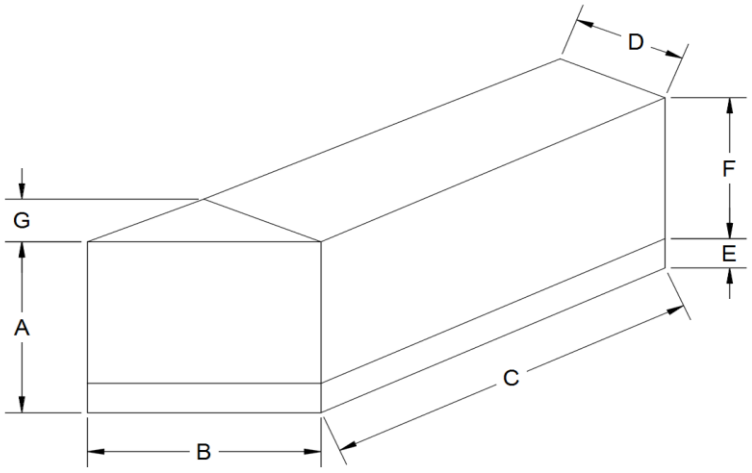

Figure 6: The facility buildings are single gable greenhouses. Dimensions (A-G) vary based on building type (acclimation, fingerling, growout, or purging building).

[5] Another feasible option would be the conversion of an existing fowl farm. The greenhouse design approach was elected because of its ability to reduce light and heating costs.

[6] Sumner (2000) explained that heating requirements can be drastically reduced when the buildings are joined as gutter connected gable greenhouses, for single buildings because of the increased risk of spreading contamination that incurs when buildings share a common wall.

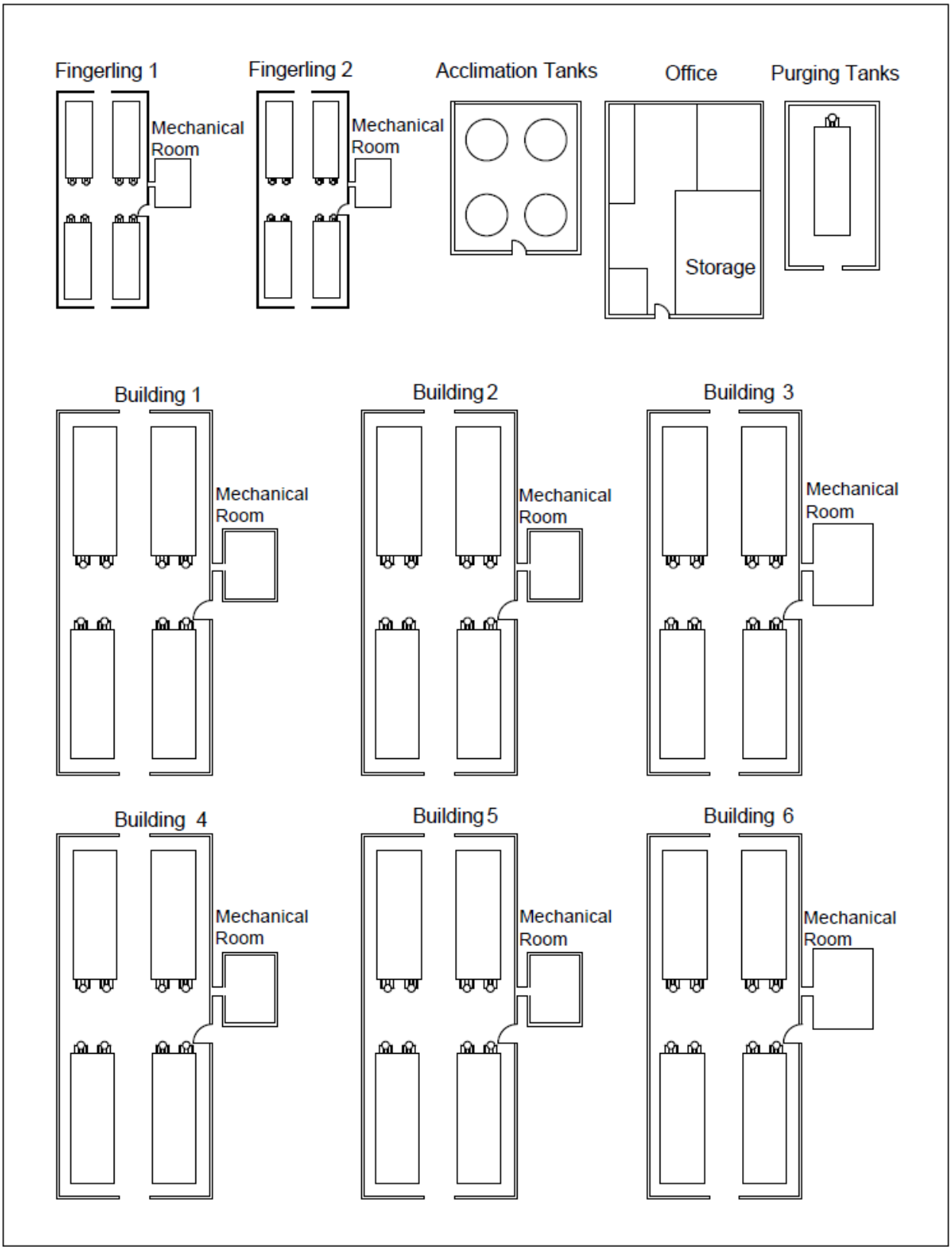

Figure 7: Layout of the proposed facility

The farm campus consists of 1 concrete building and 9 greenhouse buildings, including 6 for growout tanks and 2 for smaller fingerling tanks[7]. Although this is a growout facility, it features an acclimation system that hosts fingerling upon arrival before they are transferred to fingerling tanks, as well as a building allocated to the fingerling to growout system. Acclimation, fingerling, and growout tanks are kept in separate buildings to impede disease communication. In addition, there is a distinct building for post-harvest purging. The facility also features an office for administrative tasks. The facility was designed for a production capacity of 1,029,800 lbs. fish per year. Lagoons are used to filter waste; they are located on the farm campus premises. They are relatively inexpensive to design and require little to no maintenance and electricity in order to remain operational (Chen et al., 1997).

4.3.1. Growout Building Layout

Each growout building has a mechanical room that contains an airlift blower, a tank aeration blower, back blowers, and .4 tanks of proportional sizes. Dimensions from Figure 6 are listed in Table 7 for growout, fingerling, acclimation, office, and purging buildings. Growout buildings are the largest in terms of surface area. This is a location where traffic (workers, fish transfer) is the most active. With an individual surface area of 6,200 ft^2, they require a total of 42,000 ft^2 of double layer polyethylene[8]. Figure 8 illustrates the growout building's layout. As it is with other buildings, the mechanical room is attached externally to the rest of the building. It is strategically situated as an extension of the alley between the two symmetrical sets of tanks, with a door immediately besides the exit.

[7] Fingerling remain in 12,000 gal tanks with each length of 30 ft. width of 10 ft. and depth of 4ft, while growout tanks have a volume of 45,000 gal with each length of 40 ft. width of 25 ft. and depth of 4.5ft.
[8] Double layer polyethylene greenhouses are characterized by 2 films separated by a layer of air for optimal light transmission and temperature control.

Table 7: Measurements from Sumner (2000) were set to accommodate the RAS configuration for growout buildings.

Description	Denotation	Fingerling Building.	Acclimation Building	Office Building	Purging Building	Growout Building
Total height	A	10 ft.	10 ft.	10 ft.	10 ft.	10 ft.
Width	B	28 ft.	25 ft.	25 ft.	24 ft.	58 ft.
Length	C	76 ft.	40 ft.	48 ft.	42 ft.	106 ft.
Roof side	D	15.5 ft.	26 ft.	14 ft.	14 ft.	30 ft.
Foundation	E	2 ft.	2 ft.	2 ft.	2 ft.	2 ft.
Above ground height	F	8 ft.	8 ft.	8 ft.	8 ft.	8 ft.
Roof height	G	6 ft.	6 ft.	6 ft.	6 ft.	6 ft.

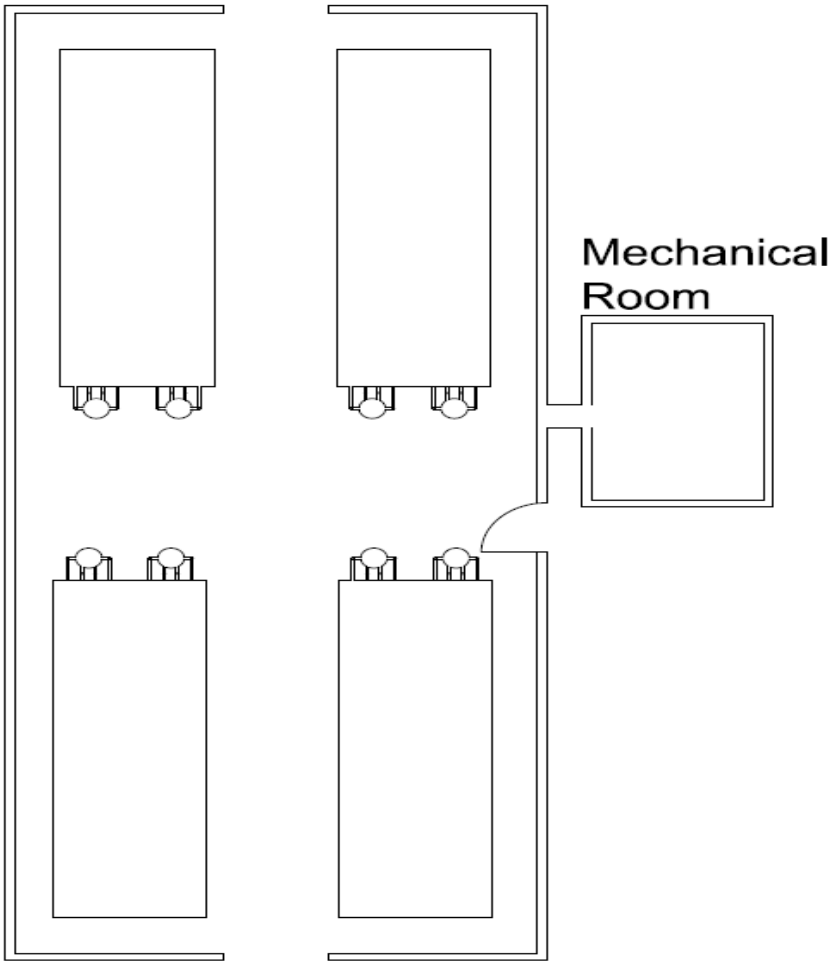

Figure 8: Layout of a growout building

4.3.2. Tanks: Characteristics and Sizing

Each growout tank has two 75 ft^2 PolyGeyser® floating bead filters and four 10 in. airlifts, each sized to circulate 375 gpm. All tanks are rectangular in shape. Tank dimensions and volume differ, depending on the production stage (acclimation, fingerling, growout). They are made of fiberglass and each one is designed with 75 aeration tubes for fingerling and purging. Acclimation tanks have 10 aeration tubes, and growout tanks have 200. Adapted from Malone (2013b), Figure 9 and Figure 10 offer a 3-D view and a side view of the tanks presented in Figure 8. They show the basic tank/filter configuration with the airlift and bead filter.

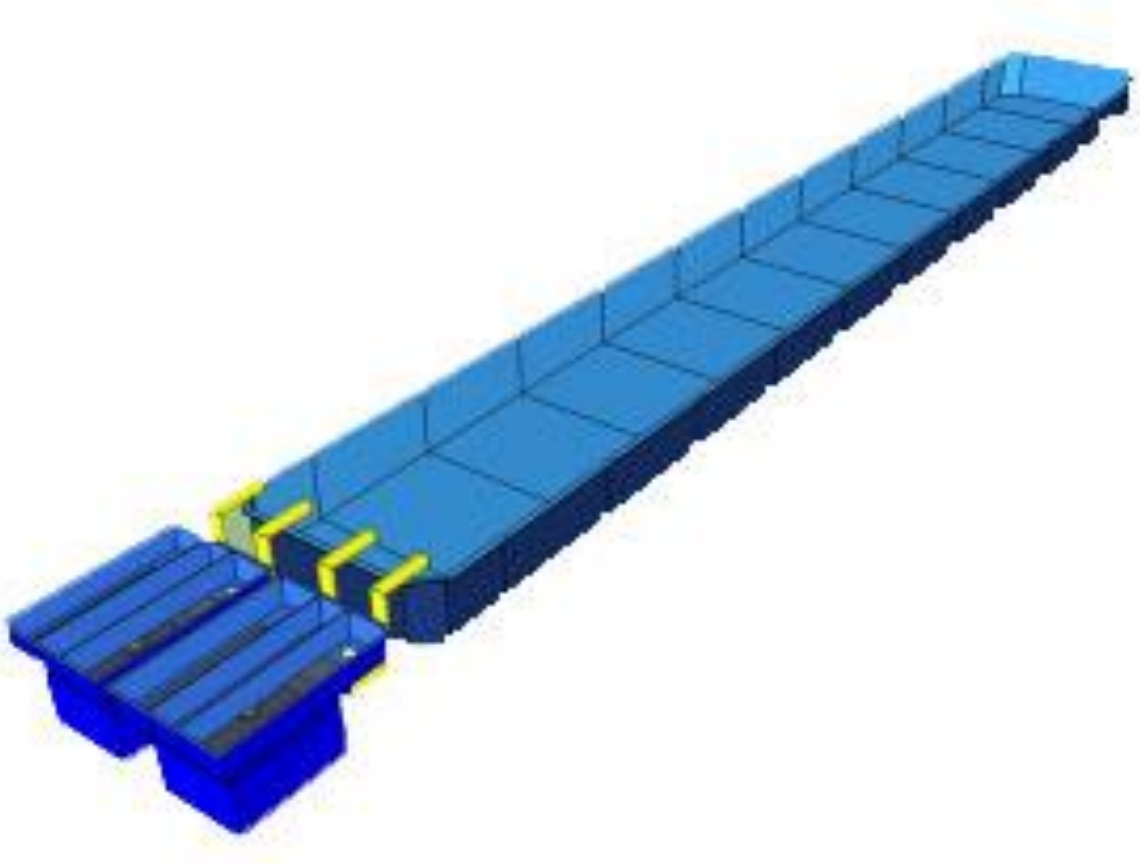

Figure 9: Each growout tank is connected to airlifts and 2 PolyGeyser® filters.

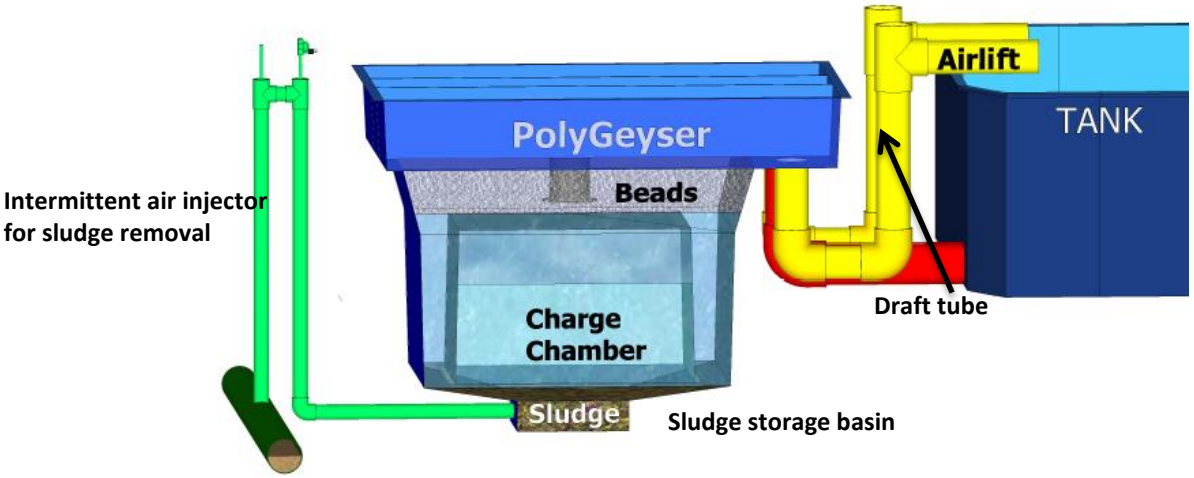

Figure 10: Schemated airlifted/PolyGeyser® combination
Adapted from Malone (2013b)

Configuration and Components

The proposing 75 ft³ PolyGeyser® bead filter models, built by Arrowhead Fiberglass Industry, LLC, located in Canton City, Colorado. The filters are filled with "Enhanced Nitrification" media configured for airlift operation produced by Aquaculture Systems Technologies in New Orleans, Louisiana. Bioclarification and recirculation in Figure 10 occurs in two modes. First, during normal operation, water travels from the tank to the PolyGeyser® through the beads to the airlift's draft tube and back into the tank. This allows the bacteria on the beads to feed off of the contaminants in the water and thus clean it. The second mode of operation is backwashing. During normal operation, air is constantly input to the charge chamber. When enough air has accumulated in the charge chamber, the air releases, forcing bubbles through the bead bed. The beads mix up and the backwash water flows into the charge chamber. As normal filtration resumes, solids settle out of the backwash water, forming a sludge in the sludge storage basin. Above this basin, each PolyGeyser® has a bottom drain located at its center. The drain is "connected to a drain line, which [discharges] solids and sludge" to a storing basin (Timmons and

Ebeling, 2006). The backwash waters are displaced by the entering air chamber. In this manner, backwash waters are recycled to the tank.

The speed of sludge flushing also depends on the hydraulic retention time (HRT), that is, the throughput flow rate or turnover time. The higher the rate, the more oxygen is provided, and the faster the sludge can be flushed away. With tanks the size of those in the proposed facility, the HRT is relatively low, compared to smaller tanks. Therefore, the airlift's inlet and outlet injection compensates for the otherwise low HRT and helps ensure proper water conditions and sludge removal (Timmons and Ebeling, 2006).

Growout Tank Design

Design constants are determined from step-by-step engineering analysis (Malone, 2013b)[9]. Each growout tank is furnished with two PolyGeyser® filters. One cubic foot of beads can process the wastes of 2.25 lbs. of feed per day under expert management. In practice, the filters operate at 67% efficiency, thus one cubic foot of beads will support 67% of 2.25 lbs. of feed, that is, 1. 5 lb. /ft^3 However, with 45,000 gallon tanks, the peak carrying capacity for feed is 225 lbs. The feed load determines the size of all components, as constants are multiplied by feed loading. Appendix C: Fingerling and Growout Assumptions shows that the recirculation rate (amount of water filtered by the PolyGeyser®) is a direct multiplication of the daily amount of feed and the constant circulation rate (amount of water per minute that moves through the airlift). In the design, we used an airflow of 3 cfm with a safety factor of 1.5. The amount of oxygen consumed is derived from the amount of feed administered. Knowing the oxygen consumed allows calculation of the RAS air flow rate.

[9] Studies such as Gudipati (2005), Hearn (2009), and Johnson (2008) provide a reliable empirical analysis framework that provides safe assumptions.

Table 8 shows the correlation between air flow and blower power (which can be translated into electricity costs). As shown in Table 9 that details the design criteria for growout tanks, we used recirculation rate of 7.5 gpm. feed/day and an airflow of 3 cfm lp feed per day and water flow rate are correlated (Malone, 2013b), calculations of the needed flow rate and the airlift cross-section area (in ft^2) will be matched with corresponding pipe diameter and length. Table 10 provides numerical values for the growout tanks' different characteristics.

Table 8: Growout air flow requirements define the blower's sizing.

Requirement	**cfm air flow**	**hp blower power**
In-tank aeration per tank	465	7
Airlifts per tank	465	7
In-tank aeration for the facility	22,300	200
Airlifts for the facility	22,300	200

Table 9: Growout airlifted PolyGeyser® design criteria adapted from Malone (2013b)

Component	Criterion	
	English Units.	Metric
Tank (recirculation rate)	200 gal./lb. feed/day	1.67 m^3/kg feed/day
PolyGeyser®	0.67 ft^3-beads/lb. feed/day	0.042 m^3 bead/kg feed/day
Recirculation flow	7.5 gpm/lb. feed/day	38 Lpm/kg feed day
Airlift area	1.5 ft/sec or 450 gpm/ft^2	0.46 m/sec
Lift (L)	12-15"	30-38 cm
Submergence (S)	4*L	4*L
Blower Volume	3 cfm/1b feed/day	187 Lpm/kg feed/day
Blower Pressure	5*L	5*L

Table 10: Physical description of RAS growout

Parameters	Amount/ Unit	Size	Units
Filter (PolyGeyser®)	2	75	ft^3 beads
Airlift	4	10	in.
Air blowers pump	1	6	hp.
Approach PVC pipes	2	10	in.
Aeration tubes	200	2	cfm rating
Backwash blowers	1	1/8	hp.
Tank	1	45000	gal.

Acclimation Tank Design

The acclimation RAS was designed to accommodate the fingerling amount of 550,038, which is derived from the desired amount of growout to full capacity. The amount of fingerlings and the corresponding acclimation tank's volume is determined considering a 10% mortality rate in both the fingerling and growout cycles.

Fingerling Tank Design

Table 11 provides calculated numerical values for the different fingerling tanks' characteristics, based on the management plan's equations detailed in Appendix C: Fingerling and Growout Assumptions. With a task volume ratio of 300 gal. /lb. feed which has been modified from the 400 gal. /lb. feed (Malone and Gudipati, 2005), the fingerling RAS design feed rate is set at 50 lbs. feed/day/ for a 12,000 galllon tank. Table 11 summarizes the tank's components. It uses less than half the amount of aeration tubes as a growout tank. The fingerling tank requires a bead volume of 100 ft^3/lb. that is, about half of the amount required in growout tanks.

Table 11: Physical description of a fingerling tank

Parameters	**Amount/ Unit**	**Sizing**	**Units**
Filter (PolyGeyser®)	2	50	ft³ beads
Airlift	2	8	in.
Air blowers pump	1	4	hp
Approach PVC	2	8	in.
Aeration tubes	75	2	cfm rating
Backwash blowers	1	(1/8)	hp
Tank	1	12,000	gal

Purge RAS Design

The calculated weekly harvest amount for the facility is 10,578 growout fish. These are transferred to the purge tanks, where the fish are no longer fed. This means that the ammonia derived from their excretions is smaller than the amount from the tilapia excretions in the growout tank. Drennan et al. (2006) detailed the AST method. The required filter's bead volume (V_b) in ft³ is calculated using the VTR (volumetric TAN conversion rate) and the biofilter's TAN removal rate R_{TAN} (Malone and Beecher, 2000; Drennam et al., 2006):

$$V_b = \frac{R_{TAN}}{VTR}$$

$$R_{TAN} = f(W)E$$

Where

f = fraction of feed over fish body weight

W = fish body weight

E = excretion rate of nitrogen per kg feed

VTR = 1000 g N

We proceed to the following calculation:

$$R_{TAN} = \left(\frac{10{,}578 \text{ fish}}{\text{tank}}\right)\left(\frac{850 \text{ g}}{\text{fish}}\right)\left(\frac{0.005 \text{ g feed/day}}{1 \text{ g fish}}\right)\left(\frac{30 \text{ g N}}{1000 \text{ g feed}}\right) = 1349 \text{ g N/tank/day}$$

$$V_b = \left(\frac{1349 \text{ g N}}{1 \text{ day}}\right)\left(\frac{\text{m}^3}{1000 \text{ g N}}\right)\left(\frac{35.5 \text{ ft}^3}{\text{m}^3}\right) = 49 \text{ ft}^3$$

Assuming that 0.5% feed rate equivalent for the purging tank yields a 49 ft.^{3} bead filter volume or approximately 50 ft^3 PolyGeyser®. This approach defines the design rationale for the purge tank RAS design.

4.3.3. Management and Production Schedule Leading to Harvest

For simplicity purposes, we assume a monosex culture of male Nile tilapia fingerlings only (Gabbadon et al., 1998). Outsourced fingerlings are placed in an acclimation tank where they remain for one week. On week 2, fingerlings at 16 grams each are divided into 4 equal amounts and transferred into 4 fingerling tanks, where they stay for 21 weeks. By that time, they reach an average weight of 70 g and have grown above 2.5 cm total body length (Bocek, 2009; Abernathy, 2015). On week 21, the fish are divided into 2 equal amounts and transferred into 2 growout tanks at a weight of 70 g, where they stay for 21 weeks until harvest. By the end of week 42, fish have reached a weight above 850 g (Diana, 1996; Abdel-Hakim et al., 2008)[10]. They are placed in a purging tank where they cleanse by excreting remaining waste for one week. The total growout time is 42 weeks, and its first harvest occurs on the first day of week 43. However, since the fingerling and growout cycle are concurrent, a harvest cycle is completes every 20 weeks.

[10] Although tilapia continues to grow after week 45, their feed conversion slows down. Keeping the fish in the growout tanks and feeding them would therefore generate financial loss (Gabbadon et al., 2008).

To maximize production, each tank remains operational on a constant basis, with the exception of 2 weeks down time after 350 days. Acclimation tanks are replenished every 4 weeks to ensure that a fingerling batch is ready as soon as harvest occurs. Table 12 illustrates how fingerling and growout schedules overlap to ensure constant operation. Completing a growout cycle from 70 g to 850 g (or 1.87 lb.) takes 21 weeks, leading to 2 entire harvests (plus 65% of a third growout cycle) within a year.

Table 12: The startup of tanks is staggered to ensure a steady output of harvest fish.

Cycle 1	Cycle 2	Cycle 3	
Acclimation Start at: week1 Duration 1 wk.: out at 5g			One year
Fingerling Start at: week 2 Duration. 20 wks.: out at 70g	Acclimation Start at: week1 Duration 1 wk.: out at 5g		
Growout Start at: week 22 Duration. 20 wks.: out at 850g	Fingerling Start at: week 2 Duration 20 wks.: out at 70g	Acclimation Start at: wk.1 Duration 1 wk.: out at 5g	
Purge Start at: week 42 Duration. 1 wk.: out at 850g	Growout Start at: week 22 Duration. 20 wks.: out at 850g	Fingerling Start at: week 2 Duration 20 wks.: out at 70g	
Harvest, loading dock	Purge Start at: week 42 Duration. 1 wk.: out at 850g	Growout Start at: week 22 Duration. 20 wks.: out at 850g	
	Harvest, loading dock	Purge Start at: week 42 Duration. 1 wk.: out at 850g	

The design criteria and management plans for fingerling and growout systems are based on a goal of harvesting 1,029,800 lbs. fish per year, that is, 550,038 fish weighing an average of 1.87 lb. each. This implies the number of fingerling required each year is 610,542. The amount of fish harvested is commensurate with proper management and up keep base on disease prevention and waste water management.

4.4.Cost Analysis: Results

4.4.1. Overview

Capital or investment cost refers to the monetary amount invested into the purchase of items needed to realize a project (such as land, machinery, equipment, transportation, facility, equipment, etc.). In other words, we consider items that must be initially purchased or rented. These amounts are fixed and generally constitute one-time expenses (Boehlje and Ehmke, 2005).

Table 13: Miscellaneous building and equipment costs other than growout capital costs

Item	Cost	Comment
Fingerling Building	$44,000.00	Two Greenhouse double liner 4400 ft² × $10
Acclimation Building	$20,000.00	Greenhouse double liner 2000 ft² × $10
Purge Building	$10,000.00	Greenhouse double liner 1000 ft² × $10
Office / Storage Building	$43,024.04	for a 1200 ft² warehouse office
Fingerling RAS	441,700.00	Design capacity to accommodate the growout amount
Acclimation RAS	$52,020.00	Design capacity to accommodate the fingerling amount
Purge RAS	$22,920.00	Design criteria based estimated TAN excretion
Labor	$33,000.00	Labor cost for construction installation and piping fitting

Table 13 shows the building cost and basic RAS costs that drive most of capital costs not directly associated with growout production. Surface area and RAS sizing are established to accommodate desired growout amounts to full capacity (in consideration of the aforementioned mortality rates).

Operating cost refers to the monetary amount required for tilapia production once the facility is functional (labor/personnel compensation, electricity, water, etc.). This also including maintenance costs in this category, that is, costs associated with ensuring the functionality of material and equipment operation (cleaning, inspection, and repairing of material and equipment). The parameters considered for maintenance are labor (consultants, technicians, janitorial, management) and electricity (water pump, water heating and cooling).

4.4.2. Fingerling RAS costs

Fingerling capital costs

Table 14 details the parameter pricing toward the capital cost of one fingerling tank. Numbers are to be multiplied by four in each building, since there are 4 tanks per building. Additionally, the design criteria indicate that two such buildings are required. Therefore, fingerling capital costs in table 14 fifth column that is multiplied by 8 (the sixth column) in order to obtain fingerling capital costs for the entire facility.

The capital costs associated with a single fingerling RAS as described in Table 11. The total capital, one-time cost for the fingerling section of the facility is $493,720. Tanks are custom-built. The cost associated with this feature is the building cost of previously designed tanks, based on labor and material. There are four fingerling tanks in each fingerling building. Each has a volume of 12,000 gal. Long fiberglass tanks are built at a cost of $1.33 per gallon (Abernathy, 2015).

Table 14: Capital cost for two fingerling facility

Parameters	Sizing	Units	Unit Cost	RAS/Tank	Facility
Equipment					
Filter (PolyGeyser®)	100.00	ft^3	$300.00	$30,000.00	$240,000.00
Tank	12000	gal	$1.33	$15,960.00	$127,680.00
Piping PVC plus fittings	500	inches	$10.00	$5,000.00	$40,000.00
Air Stone	150		$20.00	$3,000.00	$24,000.00
Air Blowers	450	cfm	$2.40	$1,080.00	$8,640.00
Backwash Blowers	1	cfm	$175.00	$175.00	$1,400.00
Total Equipment Cost				$55,215.00	$441,720.00
Labor					
Construction installation	10	hrs.	$ 25.00	$ 250.00	$ 2,000.00
Piping fitting	30	hrs./tank	$ 25.00	$ 750.00	$ 6,000.00
Total Labor Cost				$ 1,000.00	$ 8,000.00
Building					
Greenhouse Fingerling	2200	ft^2	$10.00		$44,000.00
Total Building Cost					$44,000.00
Total Cost				$56,215.00	$493,720.00

Although fiberglass is not the cheapest material, it is one the most cost-effective and reliable (Sprague, 1973; Howick et al., 1993). The fact that recirculation tanks are designed to self-clean also reduces maintenance labor costs the construction installation (labor) and pipe fitting requires 40 man hours with approximates cost of $8,000.00 for the fingerling section. Labor can be completed by several workers simultaneously at a salary of $25.00/hr. Each tank is furnished with two 50 ft^3 PolyGeyser® filters at a unit cost of $12,000 for each tank. Each fingerling building has 4 tanks, so the fingerling filter cost for the whole facility is $240,000. The air blowers, which are determined to be set at 450 cfm with a unit cost $2.40 per cfm thus a total cost of $8,640. The least expensive building material is the metallic greenhouse (market prices range from $10 to 40/$ft^2$, which is cheaper than conventional buildings). Material is needed for an area of 4400 ft^2, and we selected the lowest material cost of $10.00/$ft^2$. Thus, two fingerling building costs $44,000.

Fingerling production

The operational costs are obtained from expenses and management plans associated with operation and maintenance. The target amount to farm is 1,029,800 pound of harvestable fish divided into 8 initial fingerling tanks. Thus, each fingerling tank provides for 3 growout tanks (with 24 growout tanks in the facility). The Table 15 details the operational expenditures associated with annual fingerling production for each tank, each building, and for the entire facility.

As indicated in Table 15, each fingerling costs $0.16, based on a 5g fingerling weight. This leads to an annual fingerling production cost at $0.52 per fingerling up to the 70g, based on the design criteria. The stocking cost for the fingerling annual production is $106,500 for the entire fingerling facility: feeding is $51,800/year, and chemical cost is $24,864 per year. The electricity, labor, and heating annual costs for each tank are estimated at $69,277, $21,600, and $4,712.50, respectfully. The miscellaneous cost is two percent of the overall fingerling cost.

Table 15: Annual operating cost for fingerling

Items	Quantity/ tank/yr.	Unit	Unit cost	Cost/ tank/ yr.	Annual cost facility
Stock	$/fingerling	$0.16	83,193	$13,310.93	$106,487.45
Electricity	kwh/tank/yr.	$0.10	86,597	$8,659.65	$69,277.23
Feed	lb.	$0.37	17,500	$6,475.00	$51,800.00
Chemical (Bi-Carb)	lb.	$0.37	8,400	$3,108.00	$24,864.00
Labor	hrs/tank/yr.	$15.00	180	$2,700.00	$21,600.00
Heating	MMBtu/yr	$12.50	47	$589.06	$4,712.50
Miscellaneous	$5,574.82				$ 4,937.91
Operational cost associated with fingerling					$284,316.00
Operational cost per fingerling					$0.5169

4.4.3. Growout

Growout capital cost

Table 16 details cost based on characteristics provided in Table 9. Growout tank design requires two 75 ft³ PolyGeyser® filters for each tank with the air blower is set at 675 cfm. The metallic greenhouse buildings was selected for the growout because it provide better heating in cold weather (as they absorb solar light and transform it into heat), which translates into savings on electricity and electricity-related costs. The total RAS equipment cost for the growout section is $1,779,880.00 where the filter (PolyGeyser®) constitutes the highest capital cost of $1,080,000. The tank cost is the second costliest component for the facility at $1,436,400. The total labor cost for pipe fitting and construction installation is approximately $24,000. This amount is obtained

based on a total of forty man hours at a salary of $25.00. To accommodate the four 45,000 gallon tanks for each growout building, the facility needs a 6,200 ft^2 area. Given a price of $10.00 per ft^2, the resulting total cost is $372,000 for the six growout buildings.

Growout production

As indicated in Table 17, annual production costs for the growout section of the facility amount to $953,140. Figure 11 is a complementary bar chart that details the distribution of annual growout production costs. Both include the stocking (fingerling) unit cost based on the production cost to reach 70g per fingerling for transfer into growout tanks. This leads to a total growout facility cost of $106,500. The feeding cost is the highest of the growout production at $496,200 which consist of both the fingerling and growout cost. The chemical and electric cost are $105,050 and $111,000 respectively. A labor cost of $64,800 was established base on the facility design. Transportation estimations in Table 17 constitute the lesser cost. This amount was estimated at the maximum rates, which means that in practice, transportation could be even less costly. In this analysis, a food conversion ratio of 1.4 was assumed (1.4 lb. of feeding per lb. of fish produced). Cost of feed was assumed at $0.37/lb. (about $0.13/lb. of fish produced).

The bi-carbonate is the same chemical as the one used for fingerlings, priced at $0.37/lb., that is, $105,050 annually for the facility. Results indicate that the proposed facility produces 1,029,800 lbs. of tilapia every year. Fingerling and growout cycles result in total production cost of $0.93 /fish. The equipment production cost is $0.26 plus the purge facility production cost at $0.01 gives an overall cost per lb. of fish at $1.19.

Table 16: Growout capital cost per facility

Item	Qty.	Unit / tank	Unit Cost	Total Cost for 1 Unit Tank	Total Cost 1 Building	Facility
Equipment						
Tank	45	Kilo gal	$1.33	$59,850	$239,400	$1,436,400.00
Filter(PolyGeyser®)	150	ft^3beeds	$300.00	$45,000	$180,000	$1,080,000.00
Air TUBE/ air stone	200	aeration	$20.00	$4,000	$16,000	$96,000.00
Piping PVC plus fittings	500	inches	$10.00	$2,000	$8,000	$48,000.00
Air Blowers	675	cfm	$2.40	$1,620	$6,480	$38,880.00
Backwash Blowers	1		$250.00	$250	$1,000	$6,000.00
Total Equipment Cost				$52,870	$211,480	$1,268,880.00
Labor Cost						
Piping fitting	20	hrs.	$ 25.00	$ 500	$ 2,000	$ 12,000.00
Construction installation	20	hrs.	$ 25.00	$500	$ 2,000	$ 12,000.00
Total Labor Cost				$ 1,000	$ 4,000	$ 24,000.00
Building						
Greenhouse Growout	6,200	Ft^2	$10.00		$62,000	$372,000.00
Total Cost per building					-	$372,000.00
Facility						
Roads	1	mi.	-	-		$ 20,000.00
Water well	1	-	-	-	-	$ 5,000.00
Land	10	acres	-	-	-	$ 30,000.00
Lagoons	1	acres	-	-	-	$ 10,000.00
Power up-grade	1	kwh	-	-	-	$ 10,000.00
Forklift	1	-	-	-	-	$ 20,000.00
Box Truck	1	each	-		-	$ 20,000.00
Total Cost						$1,779,880.00

Table 17: Annual growout production cost

Items	Quantity/ Tank yr.	Unit	Unit Cost	Cost / tank yr.	Cost/ Building yr.	Cost / Facility yr.
Stock (fingerling)		$/fingerling				106,487.45
Feed	55,125	$/lb.	$0.37	20,396.25	81,585.00	$496,154.47
Chemical	9,030	$/lb.	$0.37	$3,341.10	13,364.40	105,050.40
Electricity	17,370	kw/tank/yr.	$0.10	$1,737.01	$6,948.03	110,965.39
Labor	120.00	hrs./yr.	15.00	$1,800.00	$7,200.00	$64,800.00
Heating /gas	94.27	mi.	12.50	$1,178.40	$4,713.58	$32,994.01
Transport	300.00	MMBtu/yr.	$2.50	$750.00	$3,000.00	$18,000.00
Miscellaneous						$18,689.03
Total annual operation cost for growout						$953,140.75
Production cost per pound of fish per growout						$0.9256
Total production cost per pound of fish for the facility include equipment cost						$1.19

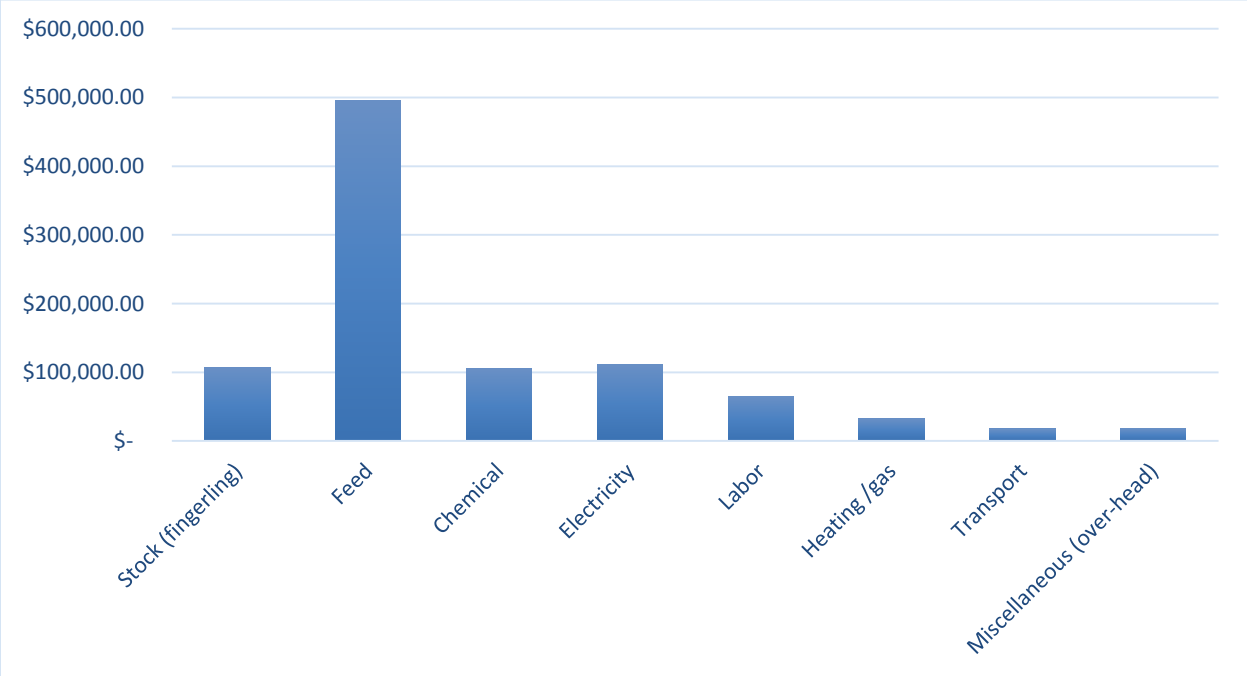

Figure 11: Distribution of operational costs associated with growout production

Greenhouse heating

Heat requirement is proportional to heat loss, which results from the difference between inside and outside temperatures. We derive our heat requirement calculations from Jones (2010) whose Excel template can be modified as the user inputs the characteristics of his facility, via the following equation:

$$Q = UA(T_i - T_o)$$

Where

Q = Heat transfer rate in BTU/hr.

U = Heat transfer coefficient (1/R value) in BTU/hr.-ft² °F;

A = Surface area in ft²;

$T_i - T_o$ = Difference of air temperature inside and outside in °F

Additional equations and calculations pertaining to the proposed facility's data input in Jones' (2010) template are located in Appendix G: Greenhouse Heating Requirements. The resulting annual greenhouse heating cost is approximately $33,300 for the facility, using natural gas for heating which based on the delivered energy per MMBTU of heat. It is based on the assumption of outside temperatures averaging 68°F in winter in Louisiana (USA Climate Data).

Airlifts: Sizing and Energy Consumption

Each tank is equipped with 2 airlift apparatuses. Using a conventional submergence to lift ratio (S: L) of 4, the submergence is 48" and the lift is 12". The water flow for the growout is 2250 gpm per tank and the gas flow (aeration) is 0.273×2250 = 615 cfm, with a gas to liquid ratio (G: L) of 2, although it is typically operated at G: L=1.3. Horsepower for a pump system such as the one for this facility is determined by Equation 1 in the Appendix D The pump efficiency and motor efficiency, given the airlift criteria are 0.8.The horsepower for one tank for one day is

therefore calculated, resulting in a value of 2.78 hp. The electric cost of airlift operation alone is $41,688.16 per facility per year. Knowing that each tank yields 42,900 lbs. fish per tank per yr. of fish upon completion of a cycle, the electricity cost is $0.10 per lb. of fish produced.

Overall labor

Regular supply of labor is required to ensure proper operation and maintenance. Thus three employees are selected to operate the facility which gives a total annual salary of $69,300.00. This don't include the engineer worker or other overhead labor cost.

4.4.4. Purge Tanks

The purge building capital cost for one 15,000 gallon tank with a 50 ft3 bead filter (PolyGeyser®). The total RAS cost of the purge building is $23,920. The building design to accommodate the purge tank is 1,000 ft2 at a cost of $10,000. The construction installation and piping fitting have a total cost of $1,000 thus a total capital cost of $33,920. Table 18 and Table 19 detail the costs associated with operation and capital.

Table 18: Annual operation costs for purge tanks

Items	Quantity/ tank/yr.	Unit	Unit cost	Annual cost facility
Electricity	21,649	kwh/tank/yr.	$ 0.10	$ 2,164.91
Labor	300	hrs./tank/yr.	$ 15.00	$ 4,500.00
Heating	24	MMBtu/yr.	$ 12.50	$ 294.53
Miscellaneous				$ 139.19
Total Cost				$ 7,098.63
Production cost/lb. for purge tank				$ 0.01

Table 19: Capital costs for purge tanks

Parameters	Sizing	Units	Unit Cost	RAS/Tank	Building
Equipment					
Filter (PolyGeyser®)	50.00	ft^3	$300.00	$15,000.00	$15,000.00
Air blowers	100	cfm	$2.50	$250.00	$250.00
Air stone	25		$20.00	$500.00	$500.00
Backwash blowers	1	cfm	$175.00	$175.00	$175.00
Piping PVC plus fittings	500	in.	$10.00	$5,000.00	$5,000.00
Tank	15,000	gal.	$1.33	$1,995.00	$1,995.00
Total equipment cost				$22,920.00	$22,920.00
Labor					
Construction installation	10	hrs.	$ 25.00	$ 250.00	$ 250.00
Piping fitting	30	hrs./tank	$ 25.00	$ 750.00	$ 750.00
Total labor cost			-	$ 1,000.00	$ 1,000.00
Building					
Greenhouse fingerling	1000	ft^2	$ 10.00		$ 10,000.00
Total building cost					$ 10,000.00
Total cost				$23,920.00	$33,920.00

4.4.5. Break-Even cost

The break-even cost is the price at which the harvested tilapia must be sold in order to cover the cost of production. To break even, the tilapia produced in this facility must be sold at $2.85/lb. knowing that the current selling price starts at $2.85/lb. (Abernathy 2015), the facility

owner can expect a minimum of $2.85/lb. of tilapia sold, which is more than twice the amount of $1.19 cost to produce it.

The interest rate related to facility, equipment, and operation costs is determined to be 2.375% based on the USDA June 1, 2015 loans for equipment/livestock/ facilities rates. Table 20 breaks down the Net Present Value (NPV) for growout buildings. Table 21 details costs year after year for 30 years. Along with the variations in maintenance cost detailed in Table 22, these calculations determine the net present value NPV which is the difference between the present value of cash inflows and the present value of cash outflows. NPV is used in capital budgeting to analyze the profitability of a projected investment or project of RAS production presented in Table 20. Additional considerations included in the aforementioned over-head and miscellaneous calculations are elements such as storage and sale expenditures. The loan interest rate plays a critical role in determining the profitability of the facility. It can be calculated that a 1% increase in the loan interest rate generates a 10 cents increase in the overall production cost.

Table 20: Unit cost per building obtained from NVP

NPV	$5,683,487.30
Annuity	$267,038.12
Annual capacity in lbs.	1,029,807.69
Revenue	$2,934,951.92
Facility equivalent equipment cost per lb. of fish	$0.2593

Table 21: Life-cycle cost for the facility

Time (yrs.)	Filter (PolyGeyser®)	Air blower's pump	Air tube	Backwash blowers	Piping PVC plus fittings	Other facility cost	Tank	Box truck & forklift	Stock	Feed	Chemical	Electricity	Labor	Transport	Heating	Miscellaneous buildings	Miscellaneous RAS	Greenhouse growout	Maintenance	Total cost
0	$ 1,080,000.00	$ 38,880.00	$ 96,000.00	$ 6,000.00	$ 48,000.00	$ 115,000.00	$ 1,436,400.00	$ 48,000.00	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ 163,024.04	$ 549,660.00	$ 372,000.00	$ -	$ 4,887,415.75
1	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
2	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
3	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
4	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
5	$ -	$ -	$ -	$ -	$ 48,000.00	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 1,002,451.71
6	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
7	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
8	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
9	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
10	$ -	$ 38,880.00	$ 96,000.00	$ 6,000.00	$ 48,000.00	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 1,143,331.71
11	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
12	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
13	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
14	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
15	$ -	$ -	$ -	$ -	$ 48,000.00	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 1,002,451.71
16	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
17	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
18	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
19	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
20	$ -	$ 38,880.00	$ 96,000.00	$ 6,000.00	$ 48,000.00	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 1,143,331.71
21	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
22	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
23	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
24	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
25	$ -	$ -	$ -	$ -	$ 48,000.00	$ -	$ -	$ 48,000.00	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 1,050,451.71
26	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
27	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
28	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
29	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 954,451.71
30	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ (54,400.00)	$ 106,487.45	$ 496,154.47	$ 105,050.40	$ 110,965.39	$ 64,800.00	$ 18,000.00	$ 32,994.01	$ -	$ -	$ -	$ 20,000.00	$ 900,051.71
TOTAL	$ 1,080,000.00	$ 93,939.42	$ 231,949.18	$ 14,496.82	$ 219,106.55	$ 115,000.00	$ 1,436,400.00	$ 47,790.95	$ 2,372,905.65	$ 11,056,023.87	$ 2,340,883.33	$ 2,472,689.58	$ 1,443,966.32	$ 401,101.76	$ 735,219.65	$ 163,024.04	$ 549,660.00	$ 372,000.00	$ 425,668.62	$ 25,571,825.75

Table 22: Facility Equivalent Equipment costs over 30 year period

Year	Capital Investment	Future Expenditure	Origin of Cost
0	$5,490,759.93	$-	Initial investment cost of + operation and maintenance in period zero
1		$20,000.00	Assumed maintenance of facility
2		$20,000.00	Assumed maintenance of facility
3		$20,000.00	Assumed maintenance of facility
4		$20,000.00	Assumed maintenance of facility
5		$68,000.00	Assumed maintenance of facility plus the replacement of equipment with 5 yr. Expiration
6		$20,000.00	Assumed maintenance of facility
7		$20,000.00	Assumed maintenance of facility
8		$20,000.00	Assumed maintenance of facility
9		$20,000.00	Assumed maintenance of facility
10		$208,880.00	Assumed maintenance of facility plus the replacement of equipment with 5 & 10 yr. Expiration
11		$20,000.00	Assumed maintenance of facility
12		$20,000.00	Assumed maintenance of facility
13		$20,000.00	Assumed maintenance of facility
14		$20,000.00	Assumed maintenance of facility
15		$68,000.00	Assumed maintenance of facility plus the replacement of equipment with 5 yr. expiration
16		$20,000.00	Assumed maintenance of facility
17		$20,000.00	Assumed maintenance of facility
18		$20,000.00	Assumed maintenance of facility
19		$20,000.00	Assumed maintenance of facility
20		$208,880.00	Assumed maintenance of facility plus the replacement of equipment with 5 & 10 yr. expiration
21		$20,000.00	Assumed maintenance of facility
22		$20,000.00	Assumed maintenance of facility
23		$20,000.00	Assumed maintenance of facility
24		$20,000.00	Assumed maintenance of facility
25		$116,000.00	Assumed maintenance of facility plus the replacement of equipment with 5 yr. expiration
26		$20,000.00	Assumed maintenance of facility
27		$20,000.00	Assumed maintenance of facility
28		$20,000.00	Assumed maintenance of facility
29		$20,000.00	Assumed maintenance of facility
30		$(34,400.00)	Assumed maintenance of facility plus the replacement of equipment with 5 & 10 yr. expiration

4.4.6. Sensitivity Analysis

A sensitivity analysis was conducted to establish the impact of interest rate on present worth (PW), annual worth (AW), and future worth (FW). The current USDA interest rate is at 2.375% for farm operations.

Present Worth

The PW shows the value of the life-cycle cost of the facility at time zero, based on interest rate. It measures the amount of money the facility owner would be able to afford to pay for the investment beyond its initial cost. Figure 12 is a graph of the PW; the negative slope indicates that the higher the interest rate, the less value of the initial asset (the facility). Each data point is calculated over a period of 30 years, which is the lifetime of the facility. The higher the interest rate, the less money it can yield at time 0.

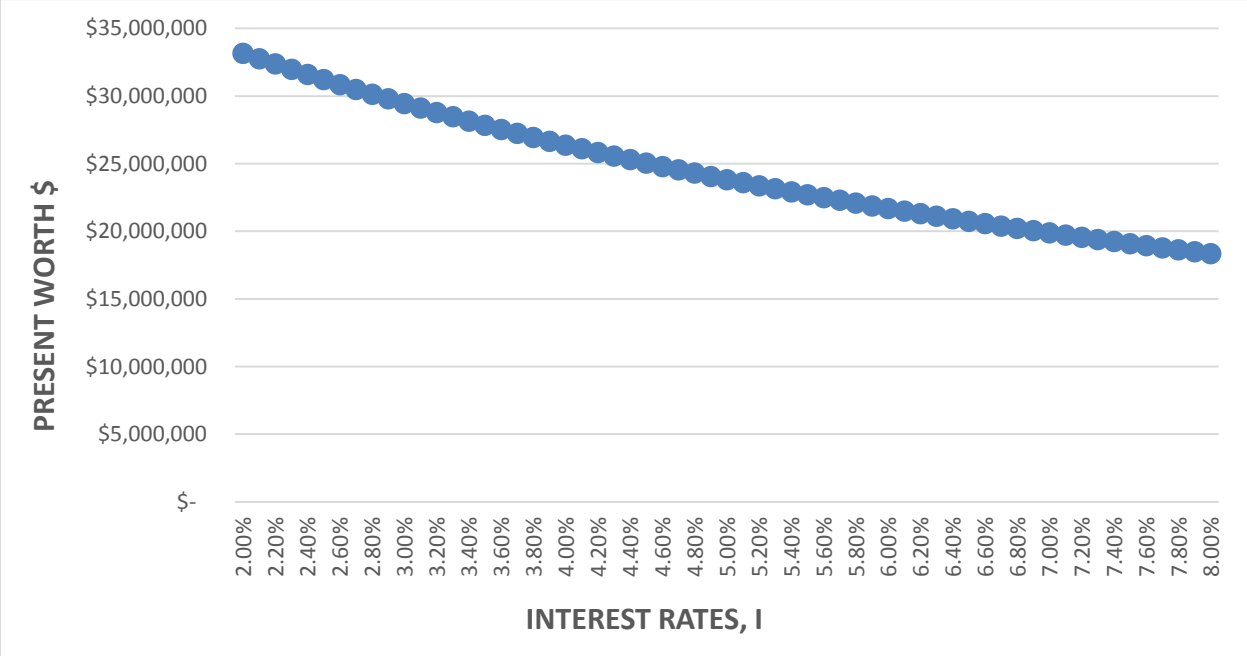

Figure 12: The present worth decreases as the interest rate increases.

Annual Worth

The AW is calculated as the PW at increasing interest rate at period t. It is calculated as the product of PW and capital recovery, which is the annual amount needed to cover loss in the asset's value and the interest in invested capital (Sullivan et al., 2003). Figure 13 shows that an increase in interest rate is associated with an increase in AW. Sullivan et al. (2003) explained that "as long as the AW is greater than or equal to zero, the project is economically attractive." Therefore, even with an increased interest rate and subsequent decreased PW, the facility remains a very lucrative proposition. This is better for the lender; the higher the interest rate, the more the borrower has to pay.

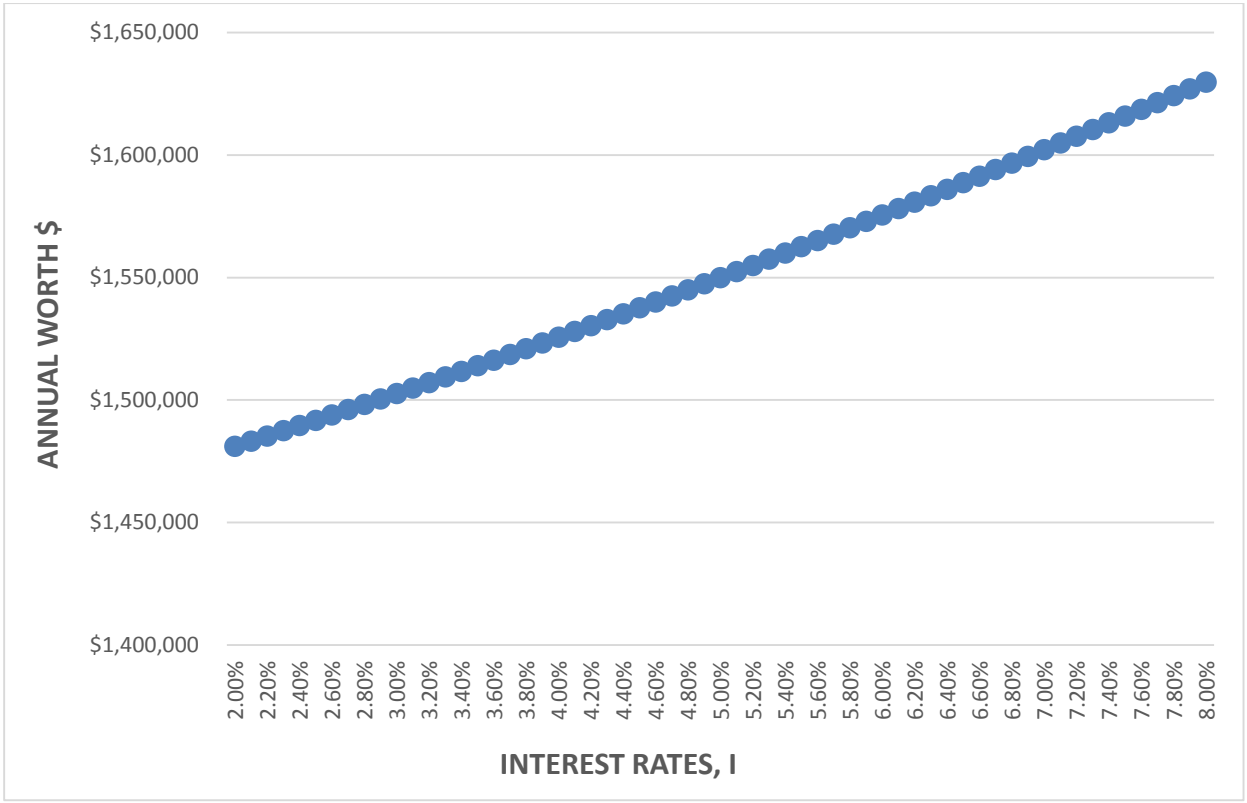

Figure 13: The annual worth increases as interest rate increases.

Future Worth

The FW is calculated as the product of AW and the uniform series compound amount factor provided in The above equations from Oregon State University Energy Efficiency Reference (2014) show the application of the heat requirement calculations in a sample automatic, computer-generated professional report.

Appendix H: Sensitivity Analysis Formulae. Figure 14 indicates the extent to which the facility's future worth increases as the interest rate increases. For a project to be economically justified, it must be more than or equal to zero. Figure 14 shows that even with higher interest rates, the tilapia production facility remains not only viable, but profitable. The cash flow for the borrower will be higher and the borrower will pay more. The lower the rate is better for the borrower, the higher is better for the lender. If the rate is higher, the capital will be less.

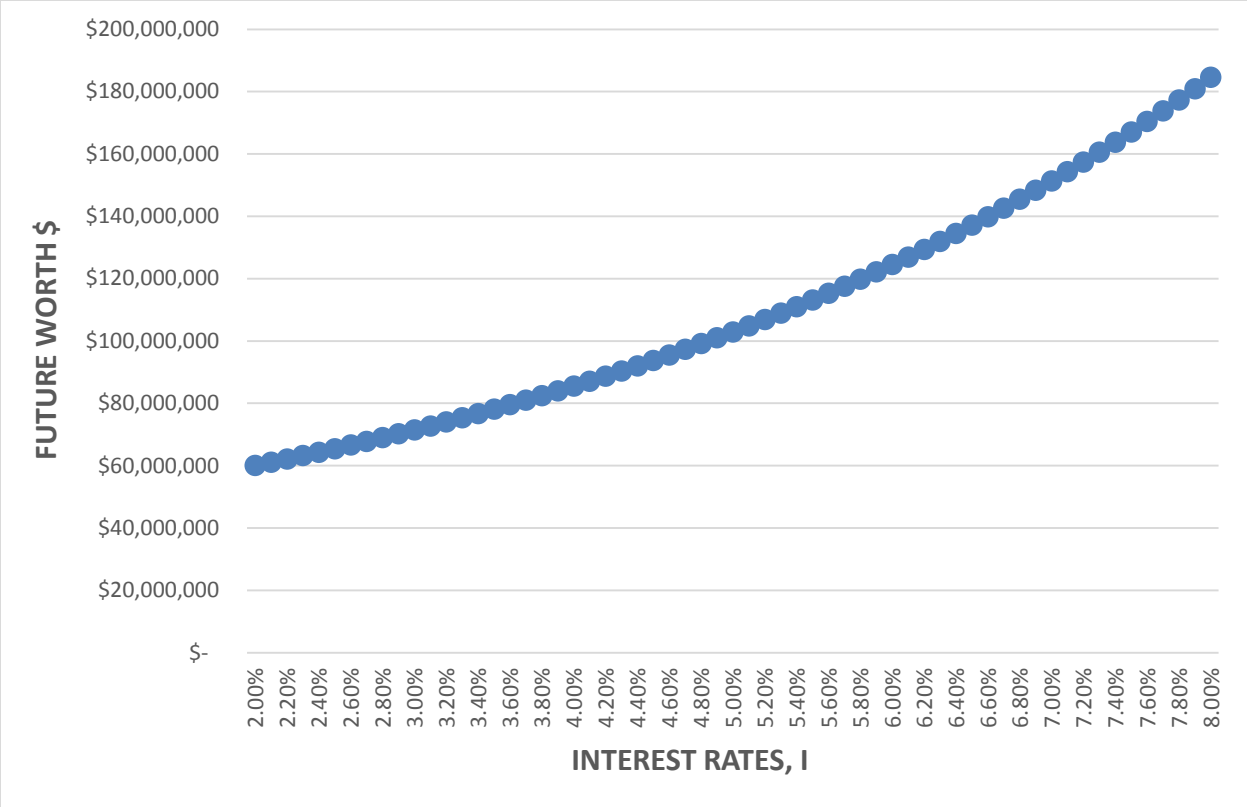

Figure 14: The future worth increases as the interest rate increases.

4.4.7. Life Cycle Cost Analysis

details the life-cycle cost (LCC) of facility, that is, costs associated with 24 tank's production and six growout building's operating over a period of 30 years. Filters and tanks have a life expectancy of 30 years. Given that, a life-cycle cost (LCC) analysis allows us to derive initial and future expenses. The rationale for the LCC is derived from Barringer (2003) who provides a framework for project and maintenance engineering, the Alaska DEED (1999) who provides a framework for building LCC's, and the Illinois CDB (1991) who provides an LCC scope for energy consumption. Although costs were previously determined in terms of net present value

(NPV), one must note that the value of the land, building, and equipment are subject to change over time due to depreciation and appreciation. Similarly, market trends for any purchased materials and paid services (fish, fingerling, feed, chemicals, equipment maintenance, and labor) might impact the aforementioned results. As indicated in the following equation, the life-cycle cost is determined as the sum of capital and annual costs over a period of 30 years

$$\mathrm{LCC} = -\sum_{t=0}^{n} \mathrm{B_t}(\frac{\mathrm{P}}{\mathrm{F}}, \mathrm{i\%}, \mathrm{t}) - \sum_{t=0}^{n} \mathrm{E_t}(\frac{\mathrm{P}}{\mathrm{F}}, \mathrm{i\%}, \mathrm{t}) - \sum_{t=0}^{n} \mathrm{M_t}(\frac{\mathrm{P}}{\mathrm{F}}, \mathrm{i\%}, \mathrm{t}) - \sum_{t=0}^{n} \mathrm{C_t}(\frac{\mathrm{P}}{\mathrm{F}}, \mathrm{i\%}, \mathrm{t})$$
$$- \sum_{t=0}^{n} \mathrm{F_t}(\frac{\mathrm{P}}{\mathrm{F}}, \mathrm{i\%}, \mathrm{t}) - \sum_{t=0}^{n} \mathrm{S_t}(\frac{\mathrm{P}}{\mathrm{F}}, \mathrm{i\%}, \mathrm{t}) - \sum_{t=0}^{n} O_{\mathrm{t}}\left(\frac{\mathrm{P}}{\mathrm{F}}, \mathrm{i\%}, \mathrm{t}\right) + SV$$

LCC= $32,216,000

Where:

P = Present value;

f = Future value;

i = Real discount rate;

SV= Salvage value;

t = Time (expressed as number of years);

B_t = Building cost (fingerling, growout, office, etc.) in period t;

E_t = Equipment (RAS) cost (filter (PolyGeyser®), tank, air blowers, etc.) in period t;

C_t = Chemical cost in period t;

F_t = Feed cost in period t;

S_t = Stocking cost (cost per fingerling) in period t;

M_t = Maintenance cost (replacement cost and maintenance) in period t;

O_t = Operation cost (labor, transportation, heating...etc.) in period t

Based on the 2014 USDA data, agriculture loans are set at a typical rate of 2.375%. The life cycle cost of the proposed facility was therefore calculated to be $32,216,000. Figure 15 shows the distribution of the major cost of the facility on a pie chart over the period (t) of 30 years.

The consumable cost, which includes the stocking, feeding and chemical cost, is $15,800,000 at 62 percent of the entire life cycle cost in which the feeding cost is a little over $11,056,000. The stocking cost is the second highest at $2,373,000 and the chemical is third part of the consumable cost at $2,341,000.00 and the fifth highest among the LCC. The operation cost and equipment cost is the third and fourth highest at $5,053,000 and $3,788,000. The building, and maintenance cost follows at $535,000, and $426,000.

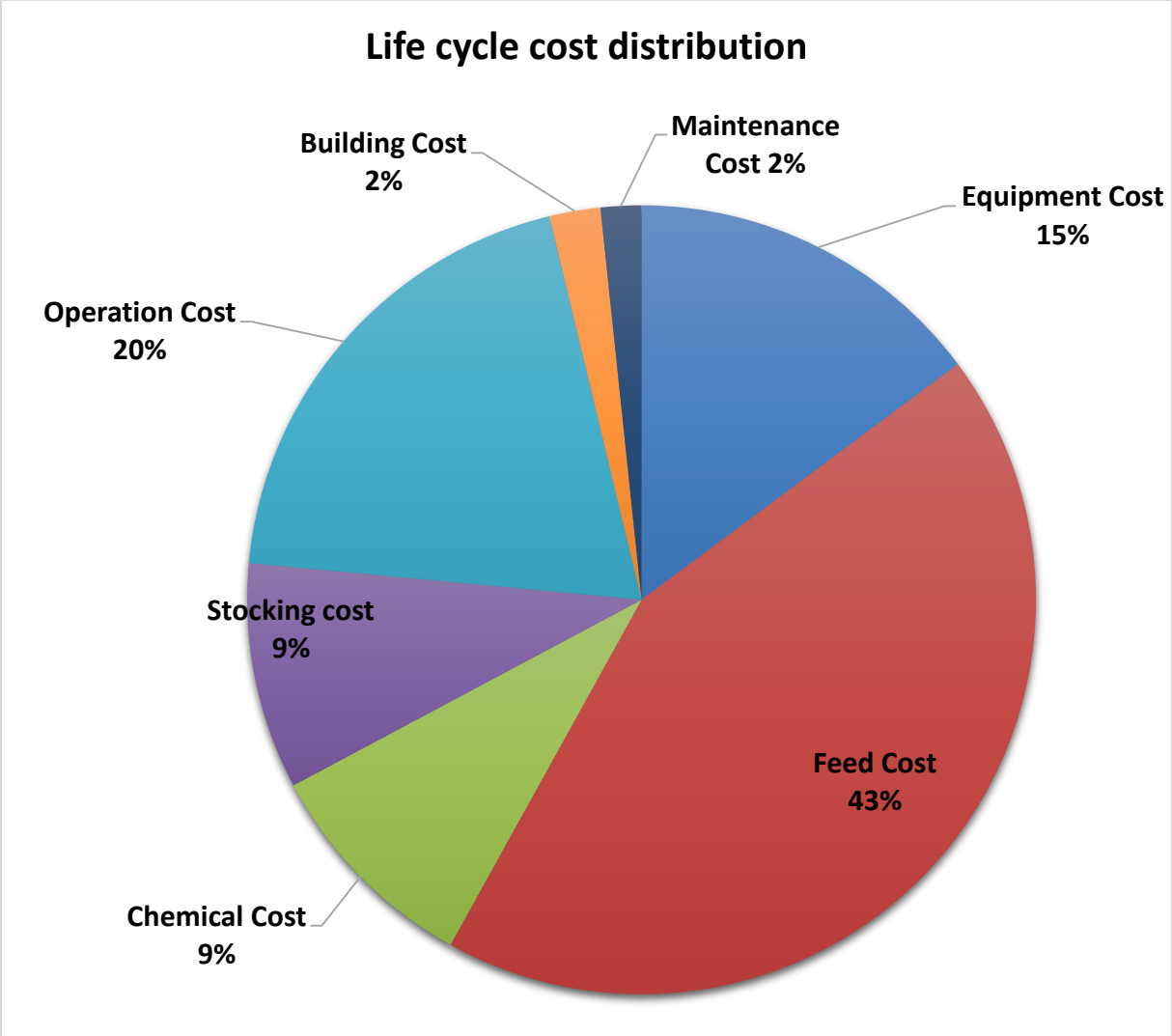

Figure 15: The production cost is calculated to be $1.19/lb. before processing. This figure breaks down the cost into 7 different categories.

4.5.Discussion and Conclusion

This analysis enters the discussion of Eding et al. (2006) who expresses the need for studies of commercial scale RAS applications to complement empirical experience. It addresses Losordo and Westerman's (1994) call to shift research from private RAS by providing "data on the economic or engineering performance of commercial scale recirculating production systems." The model suggests that RAS system-based fish farming facilities are beneficial in terms of capital

costs, based on the facility size and the related parameters and components. This project thus constitutes a step toward the process required to proceed to large scale tilapia production. It shows the financial feasibility of intensive practice, and sets an example for budget templates and decision-making tools for potential business undertakers.

The cost analysis sets the unit cost, as per the NPV, to produce one fish at approximately $2.25 per kg. This cost is still higher than the cost for tilapia sold from China, which was priced at $1.56/kg in 2013 (Tallaksen, 2013). Nonetheless, this study comes at a time when China's tilapia supply is decreasing as a result of the virus outbreak that affected the country's poultry and swine industries. Consequently, Chinese tilapia prices are on the rise (Stewart, 2013), which makes domestic production even more competitive.

The proposed facility has a considerable margin of safety and room for production increase. The filter runs at a very low density loading. Thus, an alternative management plan could involve the formation of tilapia generation pools, or cohorts, or a cross-flow system. These alternative set-ups would increase production significantly and would remarkably help save electricity-related costs. The cohort system refers to having different sized fish staggering. This alternative plan is detailed in Appendix E: Optional cohort design criteria. A cross-flow system involves different tanks running into each other. Cohort and cross-flow systems can help increase production up to 30% for the facility. Nevertheless, the cross-flow system is a gamble in the sense that any contagious disease emerging into the tank is destructive for the whole building or facility. Future work, such as the research and calculations of Alt (2015) could help determine proportionality between safety factor and cohort management variables. Evidently, the risk of fish disease is present in this proposed facility as well, but the separate tanks and buildings it features help

mitigate the consequences of an outbreak. Another risk to consider is the constant possibility of human error, particularly with chemical and feeding dosage.

A weakness of the proposed facility is that despite the fact that the RAS provides for a smaller capital cost, substantial profit relies on managing the system well at decrease in market prices or in demand would make it hard to break even. It would only exacerbate the threat of competition and large-scale imports that is already hindering domestic tilapia production. Consequently, fluctuations of the cost of feeding and electricity would affect its ability to subsist. In addition, the system does not offer much room for detailed and considerably specific improvement research, since key equipment (filters, blowers, etc.) comes in fixed-size and fixed-capacity sets (they are classified in size, efficiency, and capacity ranges, not with custom-built features).

It has already been established that RAS lower water demands and feed-generated wastes. The recommended follow-up to this study would be a planning stage (Helfrich and Garling, 2009). Such planning is potentially quite exhaustive since so many different biological, economic, and legal factors must be taken into consideration. Gutierrez-Wing and Malone (2006) who present future trends in RAS production explain that future research should "define the cost-competitiveness of growout facilities."

This next step should also include comparisons with other tilapia production facilities to assess how beneficial the proposed facility has the potential to be. For instance, the facility proposed in this thesis is capable of producing 1,053,500 lbs. of tilapia annually. Yet, aquaculturists classify different growout system sizes and harvest amounts, designated as

-small system: <1,000,000 lbs. harvested yearly

-medium system: 1,000,000-5,000,000 lbs. harvested yearly

-large system: 5,000,000 lbs. and above harvested yearly (Malone, 2015)

At this point, the analyzed facility relates to the small system category. Evidently, the amount produced via Airlifted PolyGeyser® RAS has great potential in comparison to the massive production systems in China mentioned in Section 4.2. Increasing production size will allow the production capabilities to exceed the massive import requirements of tilapia in America. In conclusion, Airlifted PolyGeyser® RAS technology is an innovative way of meeting the demand here at home and supply for future exports.

5. Conclusion

This thesis dealt with the three major aspects of aquaculture production systems for monocultures, as defined in RUFORUM (2011): cultured species, culture facility, and husbandry. Centered on airlift assisted RAS, it expanded from species-specific water quality management to intensification, that is, "producing more fish with less water, less food, and less time to lower production costs and reduce pollutants to the environment" (Watanabe et al., 2002). The two studies examined the tank filtration need and the cost of aquaculture production

Airlifted RAS have the advantage of providing a more controlled environment for the cultured species. Indeed, as RAS are acknowledged for their biosecurity, airlifts help maintain proper pH and degasification. Biofilter-equipped RAS address environmental concerns mentioned buy aqua-culturists and environmentalists: water quality, quantity, and discharge limitations, as well as pollution (Gutierrez-Wing and Malone, 2006). Nevertheless, biosecurity needs vary depending not only on the species cultured, but also its developmental stage. The egg loading data collected in this thesis is useful in hatchery RAS design. We recommend further studies on water quality at the larval stage.

Similarly, RAS production management unto the growout level differs from species to species. Data obtained on numerous variables to determine the cost of tilapia production is applicable to other species. One could also use the Chapter 3 (egg loading data) and Chapter 4's cost analysis to establish sizing criteria for the increasing demand for oligotrophic marine nurseries and growout tanks and facilities by extension (Gutierrez-Wing and Malone, 2006).

Although the majority of Latin America and Caribbean tilapia producers utilize pond systems, RAS are increasingly competing with ponds in the U.S. Large-scale commercial farming is indeed a growing trend. As U.S. and world population and per capita seafood consumption grow,

the demand for large-scale aquaculture is intensified. This thesis' cost analysis concludes that RAS can be cost-efficient, although no conclusions were drawn on fish quality upon growout with RAS v. ponds. Yet, Helfrich and Libey's (1991) observations indicated that better fish taste may translate into higher demand for RAS-produced tilapia, which could generate higher profit for domestic industries.

The cost of RAS production can be expected to decrease in the future, not so much because of investment cost, but rather because of the continual research and refinement of treatment technology. In effect, contemporary aquacultural engineering seeks to produce more energy efficient devices, and fishery and marine studies seek to produce feed with better feed conversion ratios. These two variables have the largest impact on fish production, and are key to reducing production cost.

From a long-range perspective, this study provides the background work and technical tool required for the commercial aquaculture of different species in corresponding facilities, as it contributes to determining the financial and biologic feasibility of such a trade. Indeed, Helfrich and Garling (1985) explained that commercial aquaculture is completed in four major stages. First, the planning stage constitutes the preliminary research to check the economic and biologic feasibility of the project and to examine any legal constraints. Then, the training stage involves water management and fish biology and culture. The training stage is followed by small scale production and commercialization, including one or several pilot tests. Eventually, upon successful completion of the third stage, commercial operation can take place.

Although this thesis does not mirror Helfrich and Garling's (1985) entire plan, it encompasses several of the items they mention. Indeed, the egg loading study examines biological characteristics of decaying eggs and water management of biofouled water. Fahandezhsadi (2014)

provides a complementary framework. Her report provides a mathematical model that shows the exponential growth of bacteria as hatchery water undergoes TAN biofouling. Furthermore, the comparative data across species acquired in Chapter 3 provides a framework for egg substitution, whereby studies on scarce, endangered, or expensive species can be conducted on more common and affordable species that display similar loading characteristics. Substitution, along with the use of heterotrophic bacteria acclimation (Fahandezhsadi, 2014) may help reduce the cost of bead-only filters.

The corresponding filter requirement data is useable for small scale production. On the other hand, the cost analysis provides a cost estimation framework for small and larger scale production.

The use of RAS and PolyGeysers® for commercial scale aquaculture demands a meticulously designed layout. Yet, building costs associated with construction can be avoided. Utilizing existing buildings eliminates a significant portion of construction costs. The facility should be equipped with a water source. Thus, the major parts of the equipment installation are to take place in the interior of the building. The layout we have considered in this thesis is in alignment with the recent simplified set of rules established to ensure optimal performance regarding PolyGeyser®/Airlifts and similar filtration equipment (Malone and Gudipati, 2005).

As we have demonstrated, the most essential factors to be determined when elaborating a cost analysis pertain to management, that is, the steps to take to proceed to and maintain production once the physical characteristics criteria have been met. Therefore the management plan detailed in Section 4.3.3 presents the different parameters to consider and the cost associated with them. Future cost analyses should include and prioritize a similar table, adapting and modifying the initial constants.

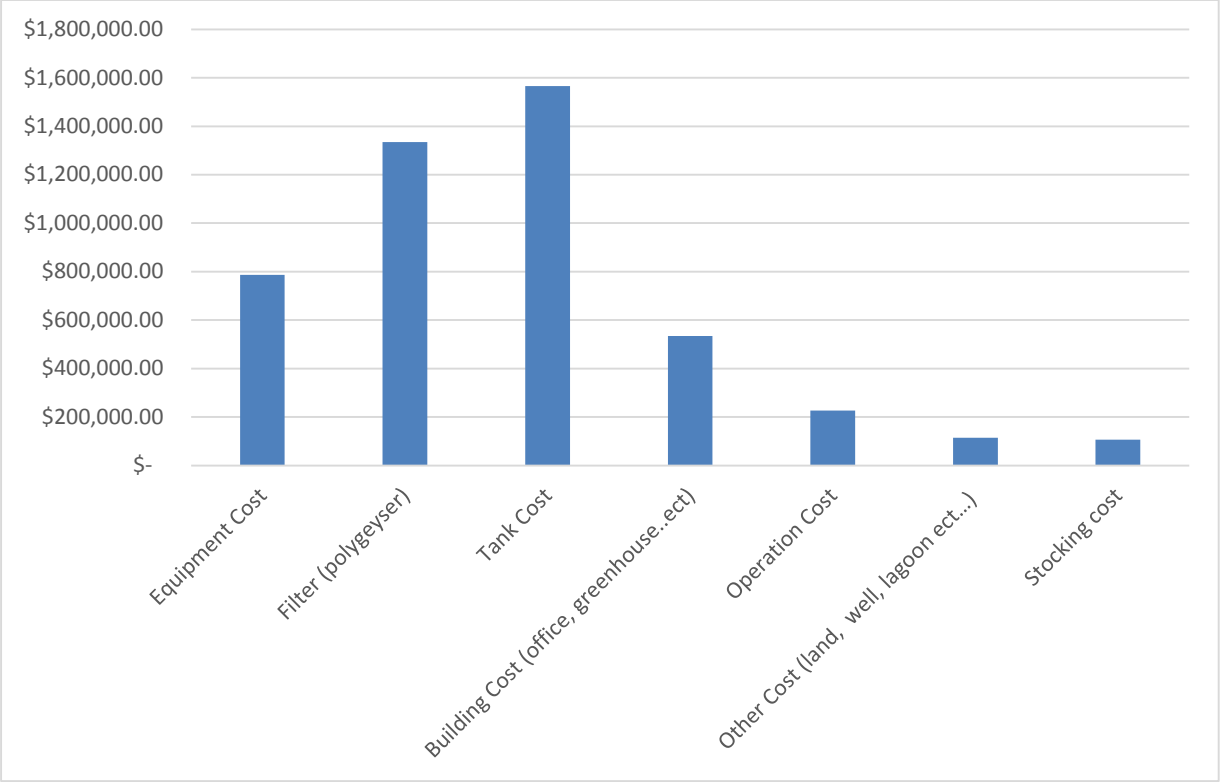

Figure 16: Distribution of operation costs for the proposed facility

Based on the LCC calculations the distribution of the operation cost shows the feeding and stocking contribute 57 percent of the entire operation cost. This is a noteworthy fact because feed cost is one of the reasons why the price of Chinese tilapia has been on the rise since the viral contamination that affected the Chinese swine and poultry industries (Stewart, 2013).

Labor represents a significant portion of the facility's operation costs. It is one of the main reasons why domestically produced tilapia is overall more expensive than tilapia produced in Third World countries from whom the U.S. imports the most. Indeed, the design set workers payment at $25/hr. for construction installation and piping fitting with a minimum general labor wage of $15/hr. Such a salary is not common practice in most Asian or South American fish production facilities (FAO, 2014).

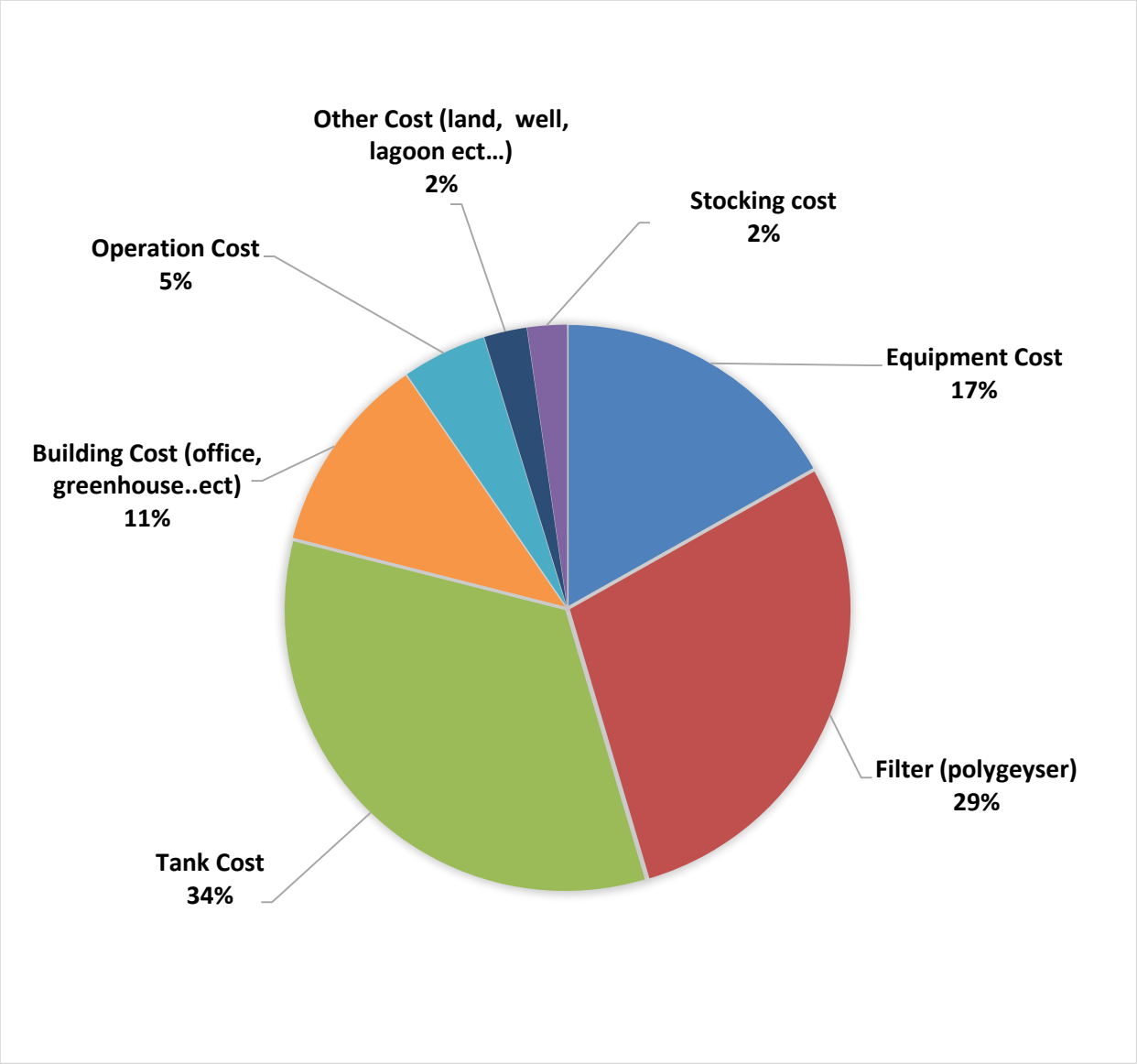

Figure 17: Distribution of capital costs for the proposed facility

Figures 16 and 17 shows the major driving cost of the operation and the capital cost of the facility. Tanks account for one third of the cost, and filters account for one quarter of the cost. This is why engineering analysis of RAS components (tanks and filters) and their sizing is crucial prior to launching a facility.

References

Abernathy, S. (2015). Personal interview. Arrowhead Fisheries. Canon City, CO.

Abdel-Hakim N.F.; Lashin, M.E.; Al-Azab A.A. and Nazmi, H.M. (2008). Effect of replacing soybean meal protein by other plant protein sources on growth performance and economical efficiency of mono sex Nile tilapia (Oreochromis niloticus) cultured in tankes.8th International Sym. on Tilapia in Aqua.2008.739-744.

Alt, D. (2015) Mass balance analysis of load leveling techniques in recirculation aquaculture systems Master's thesis. Department of Civil and Environmental Engineering. Louisiana State University. Baton Rouge, LA.

American Public Health Association. (1976). *Standard Methods for the Examination of Water and Wastewater 14ed*. APHA.

Andrews, C. (1990). The ornamental fish trade and fish conservation. *Journal of fish Biology*, *37*(sA), 53-59.

Aquaculture Systems Technologies. (2006). Bead Filter Model DF-6. Updated Version-3 09/27/06.

Armstrong, J. D., Kemp, P. S., Kennedy, G. J. A., Ladle, M., and Milner, N. J. (2003). Habitat requirements of Atlantic salmon and brown trout in rivers and streams. *Fisheries research*, *62*(2), 143-170.

Arthur, J. W., West, C. W., Allen, K. N., and Hedtke, S. F. (1987). Seasonal toxicity of ammonia to five fish and nine invertebrate species. *Bulletin of Environmental Contamination and Toxicology*, 38(2), 324-331.

Asian Institute of Technology. (1994). *Partners in Development, the Promotion of Sustainable Aquaculture.* AIT, Bangkok.

Auld, A. H., and Schubel, J. R. (1978). Effects of suspended sediment on fish eggs and larvae: a laboratory assessment. *Estuarine and Coastal Marine Science*, *6*(2), 153-164.

Awari, G. K., Ardhapurkar, P. M., Wakde, D. G., and Bhuyar, L. B. (2004). Performance analysis of air-lift pump design. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*,*218*(10), 1155-1161.

Badiola, M., Mendiola, D., and Bostock, J. (2012). Recirculating Aquaculture Systems (RAS) analysis: Main issues on management and future challenges. *Aquacultural Engineering*, *51*, 26-35.

Ball, I. R. (1967). The relative susceptibilities of some species of fresh-water fish to poisons—I. Ammonia. *Water Research*, *1*(11), 767-775.

Barringer, H. P. (2003, May). A life cycle cost summary. In *International Conference on Maintenance Societies, Perth, Australia, May*. 20-23.

Beem, M., and Hobbs, J. C. (1995). Recirculating Aquaculture Systems: Questions to Ask Before you Invest. *OSU extension facts (USA). no. F-9207.*

Bellelo, S. M. (2006). *Evaluation of Media Influence and Practical Applications for the Use of Static Low Density Media Filters in Domestic Wastewater Treatment.* M.S. Thesis. Department of Civil and Environmental Engineering. Louisiana State University. Baton Rouge, LA.

Bellido, J. M., Brown, A. M., Valvanis, V. D., Giraldez, A., Pierce G. J., Iglesias, M., and Palialexis, A. (2008). Identifying Essential Fish Habitat for Small Pelagic Species in Mediterranean Waters.

Berger, J. (1930). *U.S. Patent No. 1,759,729*. Washington, DC: U.S. Patent and Trademark Office.

Bergheim, A., Hustveit, H., Kittelsen, A., and Selmer-Olsen, A. R. 1984). (Estimated Pollution Loadings from Norwegian Fish Farms. II. Investigations 1980–1981. *Aquaculture*: 36 (1-2). 157–168.

Blaxter, J. H. S. (1969). Development Eggs and Larvae. In W.S. Hoar, D.J. Randall (Eds.), *Fish physiology, 3*. Academic Press, New York and London. 177–252.

Bocek, A. (2009). Water Harvesting and Aquaculture for Rural Development.*International Center for Aquaculture and Aquatic Environments, Swingle Hall. Auburn University Alabama*, 36849-5419.

Boehlje, M. and C. Ehmke, 2005. Capital investment analysis and project assessment. Metropolitan State College of Denver.

Bowser, P. R., Wooster, G. A., Getchell, R. G., and Timmons, M. B. (1998). Streptococcus Iniae Infection of Tilapia Oreochromis Niloticus in a Recirculation Production Facility. *Journal of the World Aquaculture Society*, *29*(3), 335-339.

Braithwaite, R. A., Carrascosa, M. C. C., and McEvoy, L. A. (2007). Biofouling of Salmon Cage Netting and the Efficacy of a Typical Copper-Based Antifoulant.*Aquaculture*, *262*(2), 219-226.

Braum, E. (1973). Einflüsse Chronischen Exogenen Sauerstoffmangels auf die Embryogenese des Herings (Clupea harengus). *Netherlands Journal of Sea Research*, *7*, 363-375.

Brindle, K., and Stephenson, T. (1996). The Application of Membrane Biological Reactors for the Treatment of Wastewaters. *Biotechnology and Bioengineering*,*49*(6), 601-610.

Brown, C. L., Power, D. M., and Núñez, J. M. (2010). 5 Disorders of Development in Fish. *Fish Diseases and Disorders*, *2*, 166.

Bruckner A. W. (2005). The importance of the marine ornamental reef fish trade in the wider Caribbean. *NOAA Fisheries*.

Bucker, B. B. (2014). Chapter 2. Climate of Louisiana. www.latech.edu/tech/liberal-arts/geography/courses/310/text/climate.

Burden, D. (1988). *Development and Design of a Fluidized Bed/Upflow Sand Filter Configuration for Use in Recirculating Aquaculture Systems*. Ph.D. Dissertation. Louisiana State University. Department of Civil Engineering.

Burrows, R. E. (1964). *Effects of accumulated excretory products on hatchery-reared salmonids*. Bureau of Sport Fisheries and Wildlife.

Carpenter, J. H. (1965a). The accuracy of the Winkler method for dissolved oxygen. *Limnology and Oceanography* 10: 135-140.

Casebolt D. B., Spear D. J., Horney B. S. Care and Use of Fish as Laboratory Animals: Current State of Knowledge. 1998.

Castilho, L.R., D.A. Mitchell, and D.M. Freire. (2009). Production of polyhydroxyalkanoates (PHAs) from waste materials and by-products by submerged and solid-state fermentation. *Bioresource Technology*, 100 (23), 5996-6009.

Chambers L. D., Stokes K. R., Walsh F. C., and Wood R. J. K. Modern approaches to marine antifouling coatings. *Surface and Coatings Technology*: 201. 2006. 3642-3652.

Chanprateep, S. (2010). Current trends in biodegradable polyhydroxyalkanoates. *Journal of bioscience and bioengineering*, *110*(6), 621-632.

Chapman, P. W. (1980). *U.S. Patent No. 4,212,268*. Washington, DC: U.S. Patent and Trademark Office.

Chapman, F. A., Fitz-Coy, S. A., Thunberg, E. M., and Adams, C. M. (1997). United States of America trade in ornamental fish. *Journal of the World Aquaculture Society*, *28*(1), 1-10.

Chen, S., Coffin, D. E. and Malone, R. F. (1997). Sludge production and management for recirculating aquacultural systems. *Journal of the World Aquaculture Society*, *28*(4), 303-315.

Chitta, B. S. (1993). Effects of backwash frequency on nitrification in plastic bead media biofilters used in recirculating finfish culture systems (Doctoral dissertation, Louisiana State University, Baton Rouge).

Choubert Jr, G., De La Noüe, J., and Luquet, P. (1979). Continuous quantitative automatic collector for fish feces. *The Progressive Fish-Culturist*, *41*(2), 64-67.

Choubert, G., De la Noüe, J., and Luquet, P. (1982). Digestibility in fish: improved device for the automatic collection of feces. *Aquaculture*, *29*(1), 185-189.

Church, B. D., Widmer, C. M. and Espinosa, R. (1977). Fungal conversion of carbohydrate wastes to animal feed protein-vitamin supplements. In *Proceedings, 8th National Symposium on Food Processing Wastes, US Environmental Protection Agency, Washington, USA*. 355-388.

Cook, F. J., Pankhurst, C. E. D Amato, C., Fanning, D. J., and Carlin, G. D. (2003). Effects of trash incorporation and soil water content on the rate of breakdown of soluble sugars in the soil following sugarcane harvest. In *Proceedings, Australian Society of Sugar Cane Technologists*. PK Editorial Services; 1999. 9-9.

Copeland, K. A., Watanabe, W. O., and Dumas, C. E. (2005). Economic Evaluation of a Small-Scale Recirculating System for Ongrowing of Captive Wild Black Sea Bass Centropristis striata in North Carolina. *Journal of the World Aquaculture Society*, *36*(4), 489-497.

Cronin, E. R., Cheshire, A. C., Clarke, S. M., and Melville, A. J. (1999). An investigation into the composition, biomass and oxygen budget of the fouling community on a tuna aquaculture farm. *Biofouling*, *13*(4), 279-299.

d'Orbcastel, E. R., Blancheton, J. P., and Aubin, J. (2009). Towards environmentally sustainable aquaculture: Comparison between two trout farming systems using Life Cycle Assessment. *Aquacultural Engineering*, *40*(3), 113-119.

Daykin, P. N. (1965). Application of mass transfer theory to the problem of respiration of fish eggs. *Journal of the Fisheries Board of Canada*, *22*(1), 159-171.

DeTolla, L. J., Srinivas, S., Whitaker, B. R., Andrews, C., Hecker, B., Kane, A. S., and Reimschuessel, R. (1995). Guidelines for the care and use of fish in research. *Ilar Journal*, *37*(4), 159-173.

Diana, J. S., Lin, C. K., and Yi, Y. (1996). Timing of supplemental feeding for tilapia production. *Journal of the world aquaculture society*, *27*(4), 410-419.

Drennan, D. G., Hosler, K. C., Francis, M., Weaver, D., Aneshansley, E., Beckman, G., Johnson, C. H. and Cristina, C. M. (2006). Standardized evaluation and rating of biofilters: II. Manufacturer's and user's perspective. *Aquacultural engineering*, *34*(3), 403-416.

Eding, E. H., Kamstra, A., Verreth, J. A. J., Huisman, E. A. and Klapwijk, A. (2006). Design and operation of nitrifying trickling filters in recirculating aquaculture: a review. *Aquacultural Engineering*, *34*(3), 234-260.

El-Sayed, A. F. M. (2006). *Tilapia culture*. CABI Publishing, Cambridge, MA.

Fahandezhsadi, F. (2014). *Assimilation, a Biological Nitrogen Removal Strategy for Freshwater Ornamental Fish Hatcheries*. Master's thesis. Louisiana State University. Baton Rouge, LA.

FAO Fisheries and Aquaculture Department. (2011). Market reports: Tilapia August 2011. United Nations.http://www.globefish.org/global-production-and-demand-for-tilapia-is-steady.html.

Fatone, F., Battistoni, P., Pavan, P., and Cecchi, F. (2007). Operation and maintenance of full-scale municipal membrane biological reactors: A detailed overview on a case study. *Industrial and Engineering Chemistry Research*, *46*(21), 6688-6695.

Food and Agriculture Organization of the United Nations 2014 fao.org/3/a-i3720e.pdf

Finn, R. N., Fyhn, H. J., and Evjen, M. S. (1991). Respiration and nitrogen metabolism of Atlantic halibut eggs (Hippoglossus hippoglossus). *Marine Biology*, *108*(1), 11-19.

Fitzsimmons, K. (2000). Future trends of tilapia aquaculture in the Americas.*Tilapia aquaculture in the Americas*, *2*, 252-264.

Fitzsimmons, K. (2004, September). Development of new products and markets for the global tilapia trade. In *Proceeding of the Sixth International Symposium on Tilapia in Aquaculture, Manila, Philippines (ed. By R. Bolivar, G. Mair and K. Fitzsimmons) pp* (pp. 624-633).

Gabbadon, P., de Souza, G., and Titus, A. (1998; Revised Edition, 2008). Tilapia farming: A manual for commercial tilapia production in Trinidad and Tobago. Institute of Marine Affairs.

Georgia Cooperative Extension. (2014).

Globefish. (2015). Tilapia Imports, March 2015. http://www.globefish.org/tilapia-march-2015.html.

Gudipati, S. (2005). *Distributed Airlift Systems Design with Application to Recirculating Soft Shell Crawfish Shedding Systems*. Doctoral dissertation. Department of Civil and Environmental Engineering. Louisiana State University. Baton Rouge, LA.

Guenther, J., Carl, C., and Sunde, L. M. (2009). The effects of colour and copper on the settlement of the hydroid Ectopleura larynx on aquaculture nets in Norway. *Aquaculture*, *292*(3), 252-255.

Guerdat, T. C., Losordo, T. M., Classen, J. J., Osborne, J. A., and DeLong, D. P. (2010). An evaluation of commercially available biological filters for recirculating aquaculture systems. *Aquacultural engineering*, *42*(1), 38-49.

Gupta, M. V., and Acosta, B. O. (2004). A review of global tilapia farming practices. *Aquaculture Asia*, *9*, 7-12.

Gutierrez-Wing, M. T., and Malone, R. F. (2006). Biological filters in aquaculture: trends and research directions for freshwater and marine applications. *Aquacultural Engineering*, *34*(3), 163-171.

Gutierrez-Wing, M. T., Rusch, K. A. and Malone, R. F. (2007). Polyhydroxyalkanoates as a carbon Source for Denitrification of Waters. In *World Environmental and Water Resources Congress 2007: Restoring Our Natural Habitat.* ASCE. 1-13.

Hai, F. I., Yamamoto, K. (2011). Membrane biological reactors. In P. Wilderer (Eds.), *Treatise on Water Science*. UK: Elsevier. 571-613.

Halachmi, I. (2006). Systems engineering for ornamental fish production in a recirculating aquaculture system. *Aquaculture*, 259(1), 300-314.

Handy RD and Poxton MG. (1993) Nitrogen pollution in mariculture: toxicity and excretion of nitrogenous compounds by marine fish. *Reviews in Fish Biology and Fisheries*: 3 (3). 205-241.

Hargreaves, J. A., Kakocy, J. E., and Bailey, D. S. (1991). Effects of diffused aeration and stocking density on growth, feed conversion, and production of Florida red tilapia in cages. *Journal of the World Aquaculture Society*, *22*(1), 24-29.

Hattori, M., Sawada, Y., Kurata, M., Yamamoto, S., Kato, K. and Kumai, H. (2004) Oxygen deficiency during somitogenesis causes centrum defects in red sea bream, Pagrus major.

Hearn, R. (2009). Gas transfer in air-lifts used to recirculate aquaculture systems. Master's thesis. Department of Civil and Environmental Engineering. Louisiana State University and Agricultural and Mechanical College.

Hearn, R. L., Pfeiffer, T., and Malone, R. L. (2008, July). The evaluation of oxygen and carbon dioxide transfer associated with airlifts in recirculating aquaculture systems. In International Conference on Recirculating Aquaculture (pp. 129-136).

Held, J. A., Malison, J. A., and Fischer, G. J. (2008). Production parameters and breakeven costs for yellow perch grow-out in recirculation aquaculture systems. Northern Aquaculture Demonstration Facility Aquaculture Publications. University of Wisconsin-Stevens Point. http://www.uwsp.edu/cols-ap/nadf/Project%20Results/Project%20Reports/Yellow%20Perch/Yellow%20Perch%20RAS%20Production%20Publication.pdf.

Helfrich, L. A. and Garling, D. L. (1985). *Planning for commercial aquaculture*. Virginia Cooperative Extension Service.

Helfrich, L. A., and Libey, G. (1991). *Fish farming in recirculating aquaculture systems (RAS)*. Virginia State Cooperative Service.

Helm, I., Jalukse, L., Vilbaste, M. and Leito, I. (2009). Micro-Winkler titration method for dissolved oxygen concentration measurement. *Analytica chimica acta*, *648*(2), 167-173.

Hodson, S. L., Burke, C. M., and Bissett, A. P. (2000). Biofouling of fish-cage netting: the efficacy of a silicone coating and the effect of netting colour.*Aquaculture*, *184*(3), 277-290.

Holliday, F. G. T., Blaxter, J. H. S., and Lasker, R. (1964). Oxygen uptake of developing eggs and larvae of the herring (Clupea harengus). *Journal of the Marine Biological Association of the United Kingdom*, *44*(03), 711-723.

Hoque, A., Awal, M., Chandra Kuri, K., and Sarker, S. (2010). Effect of salinity on the oxygen consumption of tilapia fingerlings. *World Aquaculture*,*41*(4), 15.

Horvath, L. (1981). *La Reproduction Artificielle des Poissons en Eaux Chaude: Manuel de Vulgarisation*. FAO.

Howick, G. L., deNoyelles Jr, F., Giddings, J. M. and Graney, R. L. (1993). Earthen ponds vs. fiberglass tanks as venues for assessing the impact of pesticides on aquatic environments: A parallel study with sulprofos. *Aquatic Mesocosm Studies in Ecological Risk Assessment*, 321.

Huntingford, F. A., Adams, C., Braithwaite, V. A., Kadri, S., Pottinger, T. G., Sandøe, P. and Turnbull, J. F. (2006). Current issues in fish welfare. *Journal of fish biology*, *68*(2), 332-372.

Ip Y. K., Chew S. F. and Randall D. J. (2001). Ammonia Toxicity Tolerance and Excretion. *Nitrogen Excretion*. Eds. Wright PA, Anderson PM. Academic Press. 109-140.

Johnson, B. S. (2008). *Airlift assisted wastewater treatment*. Doctoral dissertation, Louisiana State University. Department of Civil and Environmental Engineering. Baton Rouge, LA.

Johnson, D. W., and Katavic, I. (1984). Mortality, growth and swim bladder stress syndrome of sea bass (*Dicentrarchus labrax*) larvae under varied environmental conditions. *Aquaculture*, *38*(1), 67-78.

Jones, M. (2010). Insulate Greenhouse. Oregon State University Efficiency Center. https://eeref.engr.oregonstate.edu/Opportunity_Templates/Insulate_Greenhouse.

Josupeit, H. (2007). World tilapia trade. In *INFOFISH Tilapia Conference, Kuala Lumpur*.

Lee, P. G., Turk, P. E., and Whitson, J. L. (2001). *U.S. Patent No. 6,171,480*. Washington, DC: U.S. Patent and Trademark Office.

Lewis W. M. and Wehr L.W. (1976). A fish-rearing system incorporating cages, water circulation, and sewage removal. *The Progressive Fish-Culturist*: 38 (2). 78-81.

Liao, I. C., Huang, T. S., Tsai, W. S., Hsueh, C. M., Chang, S. L. and Leaño, E. M. (2004). Cobia culture in Taiwan: current status and problems. *Aquaculture*, *237*(1), 155-165.

Losordo, T. M. and Westerman, P. W. (1994). An analysis of biological, economic, and engineering factors affecting the cost of fish production in recirculating aquaculture systems. *Journal of the World Aquaculture Society*, *25*(2), 193-203.

Losordo, T. M., Masser, P. M., and Rakocy, J. E. (1992). An overview of critical considerations. Recirculating aquaculture tank production systems. Southern Regional Aquaculture Center (SRAC).

Lovegrove, T. (1979). Control of fouling in farm cages. *Fish Farming International*, *6*(1), 33-7.

Loyless, J. C., and Malone, R. F. (1998). Evaluation of air-lift pump capabilities for water delivery, aeration, and degasification for application to recirculating aquaculture systems. *Aquacultural Engineering*, 18(2), 117-133.

Lubzens, E., Young, G., Bobe, J., and Cerdà, J. (2010). Oogenesis in teleosts: how fish eggs are formed. *General and Comparative Endocrinology*, *165*(3), 367-389.

MacKenzie, B. R., Leggett, W. C., and Peters, R. H. (1990). Estimating larval fish ingestion rates: can laboratory derived values be reliably extrapolated to the wild?. *Marine Ecology-Progress Series (Halstenbeck)*, *67*(3), 209-225.

Madsen, L., and Dalsgaard, I. (1999). Vertebral column deformities in farmed rainbow trout (Oncorhynchus mykiss). *Aquaculture*, *171*(1), 41-48.

Malison, J. A., and Held, J. A. (1992). Effects of fish size at harvest, initial stocking density and tank lighting conditions on the habituation of pond-reared yellow perch (Perca flavescens) to intensive culture conditions. *Aquaculture*, *104*(1), 67-78.

Malison, J. A. and Held, J. A. (2006). Farm-based production parameters and break-even costs for yellow perch grow-out in ponds in Southern Wisconsin. *USDA Grant*, *45079*, 03535.

Malone, R. F. (1992). *U.S. Patent No. 5,126,042*. Washington, DC: U.S. Patent and Trademark Office.

Malone, R. F. (1993). *U.S. Patent No. 5,232,586*. Washington, DC: U.S. Patent and Trademark Office.

Malone, R. F. (1995). *U.S. Patent No. 5,445,740*. Washington, DC: U.S. Patent and Trademark Office.

Malone, R. F. (1998). *U.S. Patent No. 5,770,080*. Washington, DC: U.S. Patent and Trademark Office.

Malone, R. F. (2003). *U.S. Patent No. 6,517,724*. Washington, DC: U.S. Patent and Trademark Office.

Malone, R. F. (2013a). Recirculating aquaculture tank production systems: A review of current design practice. Southern Regional Aquaculture Center Publication No. 453.

Malone, R. F. (2013b). Refining design criteria for commercial scale Airlifted PolyGeyser® tilapia production. World Aquaculture Society 2013 Conference. Nashville, TN.

Malone, R. F. (2015). Personal interview. Aquaculture Systems Technologies. Baton Rouge, LA.

Malone, R. F., and Burden, D. G. (1988). *Design of recirculating soft crawfish shedding systems*. Louisiana Sea Grant College Program, Center for Wetland Resources, Louisiana State University.

Malone, R. F., and Beecher, L. E. (2000). Use of floating bead filters to recondition recirculating waters in warmwater aquaculture production systems. *Aquacultural Engineering*, *22*(1), 57-73.

Malone R. F., and Gudipati S. (2005). Decentralized water treatment in recirculating marine hatchery systems. *Proceedings of the 34th US Japan Naturl Resources Panel Aquaculture Symposium*, San Diego, California.

Malone, R. F., and Pfeiffer, T. J. (2006). Rating fixed film nitrifying biofilters used in recirculating aquaculture systems. *Aquacultural engineering*, *34*(3), 389-402.

Malone, R. F., Bergeron, J., and Cristina, C. M. (2006). Linear versus Monod representation of ammonia oxidation rates in oligotrophic recirculating aquaculture systems. *Aquacultural Engineering*, *34*(3), 214-223.

Malone, R. F., Rusch, K. A., and Burden, D. G. (1990). Kemp's Ridley sea turtle waste characterization study: precursor to a recirculating holding system design. *Journal of the World Aquaculture Society*, *21*(2), 137-144.

Martins, C. I. M., Eding, E. H., Verdegem, M. C. J., Heinsbroek, L. T. N., Schneider, O., Blancheton, J. P., Roque d'Orbcastel, E. and Verreth, J. A. J. (2010). New developments in recirculating aquaculture systems in Europe: A perspective on environmental sustainability. *Aquacultural Engineering*, *43*(3), 83-93.

Masser, M. P., Rakocy, J., and Losordo, T. M. (1999). Recirculating aquaculture tank production systems. *Management of Recirculating Systems. SRAC Publication*, 452.

Mather, F. (1884). *Progress in Fish-culture*. Century Company 27, 87.

McCormick, P. G. (1972). The determination of dissolved oxygen by the Winkler method. a student laboratory experiment. *The Journal of Chemical Education* 49 (12): 839–841.

McLeary, E. J. (1949). U.S. Patent No. 2,476,425. Washington, DC: U.S. Patent and Trademark Office.

Meade, J. W. (1985). Allowable ammonia for fish culture. *The Progressive Fish-Culturist*, *47*(3), 135-145.

Michaud, L., Blancheton, J. P., Bruni, V. and Piedrahita, R. (2006). Effect of particulate organic carbon on heterotrophic bacterial populations and nitrification efficiency in biological filters. *Aquacultural Engineering*, *34*(3), 224-233.

Milstein, A., Peretz, Y., and Harpaz, S. (2008). Culture of organic tilapia to market size in periphyton-based ponds with reduced feed inputs. *Aquaculture Research*, *40*(1), 55-59.

Molleda, M. I., Thorarensen, H., and Johannsson, R. (2007). Water quality in recirculating aquaculture systems for arctic charr (Salvelinus alpinus L.) Culture. *UNU-Fishries Training Programme. Final Project*.

Moss, S. M., and Leung, P. (2006). Comparative cost of shrimp production: earthen ponds versus recirculating aquaculture systems. In *Shrimp Culture: Economics, Marketing and Trade*, (pp. 291-300). Hoboken, NJ: John Wiley and Sons.

Muir, J., Van Rijn, J., and Hargreaves, J. (2000). Production in intensive and recycle systems. In *Tilapias: biology and exploitation* (pp. 405-445). Springer Netherlands.

Ng, P. K., and Tan, H. H. (1997). Freshwater fishes of Southeast Asia: potential for the aquarium fish trade and conservation issues. *Aquarium Sciences and Conservation*, *1*(2), 79-90.

NOAA (National Oceanic and Atmospheric Administration). Magnuson-Stevens Fishery Conservation and Management Act, as Amended Through October 11, 1996. 1996.

O'Connor, M. P., Juanes, F., McGarigal, K., and Caris, J. (2012). Describing juvenile American shad and striped bass habitat use in the Hudson River Estuary using species distribution models. *Ecological Engineering*, *48*, 101-108.

Ødegaard, H., Rusten, B., and Westrum, T. (1994). A new moving bed biofilm reactor-application and results. *Water Science and Technology (United Kingdom)*, 29(10-11), 157-165.

Oh, M. J., Jung, S. J., Kim, S. R., Rajendran, K. V., Kim, Y. J., Choi, T. J., Kim, H., and Kim, J. D. (2002). A fish nodavirus associated with mass mortality in hatchery-reared red drum, Sciaenops ocellatus. *Aquaculture*, 211(1), 1-7.

Oregon State University Energy Efficiency Center. (2014). AR No. # Insulate Greenhouse.

Otoshi, C. A., Arce, S. M. and Moss, S. M. (2003). Growth and reproductive performance of broodstock shrimp reared in a biosecure recirculating aquaculture system versus a flow-through pond. *Aquacultural engineering*, 29(3), 93-107.

Padmakumar, K. G., Bindu, L., Sreerekha, P. S., Joseph, N., Manu, P. S., and Krishnan, A. (2014). First report on captive breeding of endemic Red tailed silver shark Gonoproktopterus curmuca (Cyprinidae: Hamilton-Buchanan 1807). *International Journal of Research in Fisheries and Aquaculture*, 4(4), 156-160.

Papavlasopoulou, I., Vardakas, L., Perdikaris, C., Kommatas, D., and Paschos, I. (2013). Ornamental fish in pet stores in Greece: a threat to biodiversity? *Mediterranean Marine Science*, *15*(1), 126-134.

Parker, M., DeLong, D., Dunning, R. D., Losordo, T. M., and Hobbs, A. O. (2012). A Spreadsheet Tool for the Economic Analysis of a Recirculation Tank System. Southern Regional Aquaculture Center. Publication No. 456.

Parker, N. C. and Suttle, M. A. (1987). Design of airlift pumps for water circulation and aeration in aquaculture. *Aquacultural engineering*, 6(2), 97-110.

Peck L. S. and Uglow R. F. (1990). Two methods for the assessment of the oxygen content of small volumes of seawater. *Journal of Exp Mar Biol Ecol*, 141,53–62.

Pomeroy, R. S., Parks, J. E., and Balboa, C. M. (2006). Farming the reef: is aquaculture a solution for reducing fishing pressure on coral reefs? *Marine Policy*, *30*(2), 111-130.

Popma, T. J., and Lovshin, L. L. (1996). *Worldwide prospects for commercial production of tilapia*. International Center for Aquaculture and Aquatic Environments.

Randall, D. J., and Tsui, T. K. N. (2002). Ammonia toxicity in fish. *Marine Pollution Bulletin*, 45(1), 17-23.

Rosenberg, A., Bigford, T. E., Leathery, S., Hill, R. L., and Bickers, K. (2000). Ecosystem approaches to fishery management through essential fish habitat. *Bulletin of Marine Science*, *66*(3), 535-542.

RUFORUM (2011). Agricultural Marketing Management Module. Bunda College of Agriculture.

Rusten, B., Eikebrokk, B., Ulgenes, Y., and Lygren, E. (2006). Design and operations of the Kaldnes moving bed biofilm reactors. *Aquacultural Engineering*, *34*(3), 322-331.

Ruyet, J., Chartois, H., and Quemener, L. (1995). Comparative acute ammonia toxicity in marine fish and plasma ammonia response. *Aquaculture*, *136*(1), 181-194.

Salvesen, I., and Vadstein, O. (1995). Surface disinfection of eggs from marine fish: evaluation of four chemicals. *Aquaculture International*, *3*(3), 155-171.

Sandu S., Gregory D., Boardman G. D., Wattenc B. J., and Brazil B. L. (2002). Factors influencing the nitrification efficiency of fluidized bed filter with a plastic bead medium. *Aquacultural Engineering*: 26 (1). 41–59.

Sastry, B. N., DeLosReyes Jr, A. A., Rusch, K. A., and Malone, R. F. (1999). Nitrification performance of a bubble-washed bead filter for combined solids removal and biological filtration in a recirculating aquaculture system. *Aquacultural Engineering*, 19(2), 105-117.

Schubel, J. R. (1974). Effects of exposure to time-excess temperature histories typically experienced at power plants on the hatching success of fish eggs. *Estuarine and Coastal Marine Science*, *2*(2), 105-116.

Sharrer, M. J., Rishel, K., and Summerfelt, S. (2009). Evaluation of geotextile filtration applying coagulant and flocculant amendments for aquaculture biosolids dewatering and phosphorus removal. *Aquacultural Engineering*, *40*(1), 1-10.

Sharrer, M. J., Rishel, K., and Summerfelt, S. T. (2010). Evaluation of a membrane biological reactor for reclaiming water, alkalinity, salts, phosphorus, and protein contained in a high-strength aquacultural wastewater. *Bioresource Technology*, *101*(12), 4322-4330.

Sharrer, M. J., Tal, Y., Ferrier, D., Hankins, J. A., and Summerfelt, S. T. (2007). Membrane biological reactor treatment of a saline backwash flow from a recirculating aquaculture system. *Aquacultural engineering*, *36*(2), 159-176.

Sharrer, M., Rishel, K., Taylor, A., Vinci, B. J., and Summerfelt, S. T. (2010). The cost and effectiveness of solids thickening technologies for treating backwash and recovering nutrients from intensive aquaculture systems. *Bioresource technology*, *101*(17), 6630-6641.

Shinn, C., Marco, A. and Serrano, L. (2013). Influence of low levels of water salinity on toxicity of nitrite to anuran larvae. *Chemosphere*, *92*(9), 1154-1160.

Shnel, N., Barak, Y., Ezer, T., Dafni, Z., and van Rijn, J. (2002). Design and performance of a zero-discharge tilapia recirculating system. *Aquacultural Engineering*, *26*(3), 191-203.

Smart, G. (1976). The effect of ammonia exposure on gill structure of the rainbow trout (*Salmo gairdneri*). *Journal of Fish Biology*, *8*(6), 471-475.

Smith S. A. and Noll L. E. (2009). Testing the waters: IACUC issues associated with fish.

Southgate, P. (2010). 13 Welfare and Farmed Fish. *Fish Diseases and Disorders*, *2*, 357.

Speare, D. J. (1998). Disorders associated with exposure to excess dissolved gases. *Fish diseases and disorders*, 207.

Sprague, J. B. (1973). The ABC's of pollutant bioassay using fish. *ASTM Spec. Tech. Publ.*, (528), 6-30.

State of Alaska Department of Education and Early Development. (1999). *Life Cycle Cost Analysis Handbook*. Juneau, AK.

State of Illinois www.illinois.gov/cdb/business/Documents/FY2015%20FOIA%20Info.pdf

STECF. (2006). Report of the scientific, technical and economic committee or fisheries opinion on 'sensitive and essential fish habitats in the Mediterranean Sea.'

Steer, M. A., and Moltschaniwskyj, N. A. (2007). The effects of egg position, egg mass size, substrate and biofouling on embryo mortality in the squid Sepioteuthis australis. *Reviews in Fish Biology and Fisheries*, *17*(2-3), 173-182.

Steinke, D., Zemlak, T. S., and Hebert, P. D. (2009). Barcoding Nemo: DNA-based identifications for the ornamental fish trade. *PLoS one*, *4*(7), e6300.

Stewart, J. (2013). U.S. tilapia demand roars despite soaring prices. *Undercurent News*. www.undercurrentnews.com/2013/08/07/us- tilapia-demand-roars-despite-soaring-prices/

Sullivan, W. G., Whicks, E. M. and Luxhoj, J. T. (2003). *Engineering Economy*, 12th Ed. Prentice Hall. Upper Saddle River, NJ.

Summerfelt, S. T. (2006). Design and management of conventional fluidized-sand biofilters. *Aquacultural Engineering*, *34*(3), 275-302.

Sumner, P. E. (2000). Transplant growing facilities. University of Georgia College of Agricultural and Environmental Sciences. *Cooperative Extension Service*, Mis. Pub. No. ENG00-003.

Szluha, A. T. (1974). Potamological effects of fish hatchery discharge. *Transactions of the American Fisheries Society*, *103*(2), 226-234.

Tallaksen, E. (2013). Tilapia prices down from spring levels, but still high. *Undercurrent News*. www.undercurrentnews.com/2013/07/22/tilapia-prices-down-from-spring-levels-but-still-high/

Tangtrongpiroj M. and Chansue N. (2001).Tolerance of importance economic ornamental fish to dichlorvos. *Thai Fisheries Gazette*: 54 (2), 111-116.

Tchobanoglous G. and Schroeder E. (1985). *Water Quality*. Addison-Wesley Pub. Co.

Tessari, P. (2006). Nitrogen balance and protein requirements: Definition and measurements. In *Cachexia and Wasting: A Modern Approach*. Springer Milan. 73-79.

TheFishSite News Desk. (2007). Marine Cobia growing fast in freshwater farm. http://www.thefishsite.com/fishnews/3968/marine-cobia-growing-fast-in-freshwater-farm.

Thomasson M. P. (1991). *Nitrification in Fluidized Bed Sand Filters for Use in Recirculating Aquaculture Systems*. MS Thesis. Department of Civil Engineering, Louisiana State University, Baton Rouge, Louisiana.

Thurow, F. (1997). Estimation of the total fish biomass in the Baltic Sea during the 20th century. *ICES Journal of Marine Science: Journal du Conseil*, *54*(3), 444-461.

Timmons, M. B., and Ebeling, J. M. (2006). Culture Tank Design. University of Arizona. http://ag.arizona.edu/azaqua/ista/ISTA7/RecircWorkshop/Workshop%20PP%20%20&%20Misc%20Papers%20Adobe%202006/4%20Culture%20Tank%20Design/Culture%20Tank%20Design.pdf.

Timmons, M. B., and Summerfelt, S. T. (1998). Application of fluidized sand biofilters. In *Proceedings of the Second International Conference on Recirculating Aquaculture, Virginia* Polytechnic Institute and State University, Roanoke, VA (pp. 342-354).

Titcomb, J. W. (1910). Report of committee on breeding fish. .*Journal of Heredity*, *1*(4), 263-265.

Tlusty, M. (2002). The benefits and risks of aquacultural production for the aquarium trade. *Aquaculture*, *205*(3), 203-219.

Tomé, D. and Bos, C. (2000). Dietary protein and nitrogen utilization. *The Journal of nutrition*, *130*(7), 1868S-1873S.

Trout Unlimited. (2010). The Nitrogen Cycle. Eds. RCPS, McGarvey J. www.vctu.org/wp-content/uploads/2012/05/The_Nitrogen_Cycle.ppt.

Turk, P. E., and Lee, P. G. (1991). Design and economic analyses of airlift versus electrical pump driven recirculating aquaculture systems. *Engineering Aspects of Intensive Aquaculture*, 271-283.

USDA Economic Research Institute. (2015). U.S. tilapia imports, value by selected sources. http://www.ers.usda.gov/data-products/aquaculture-data.aspx.

USDA Economic Research Institute. (2015). U.S. tilapia imports, volume by selected sources. http://www.ers.usda.gov/data-products/aquaculture-data.aspx.

USA Climate Data http://www.usclimatedata.com/climate/louisiana/united-states/3188

Vaithanomsat, P. and Kitpreechavanich, V. (2008). Sericin separation from silk degumming wastewater. *Separation and Purification Technology*, *59*(2), 129-133.

Valavanis, V. D. Pierce, G. J., Zuur, A. F., Palialexis, A., Saveliev, A., Katara, I. and Wang, J. (2008). Modelling of essential fish habitat based on remote sensing, spatial analysis and GIS. *Hydrobiologia*, *612*(1), 5-20.

Wagener, C. (2003). *Evaluation of Static Low Density Media Filters for Use in Domestic Wastewater Treatment*. Master's thesis. Department of Civil and Environmental Engineering. Louisiana State University.

Wallace, R. A., and Selman, K. (1990). Ultrastructural aspects of oogenesis and oocyte growth in fish and amphibians. *Journal of electron microscopy technique*, *16*(3), 175-201.

Watanabe, W. O., Ellis, E. P., Ellis, S. C. and Feeley, M. W. (1998). Progress in controlled maturation and spawning of summer flounder Paralichthys dentatus broodstock. *Journal of the World Aquaculture Society*, *29*(4), 393-404.

Watanabe, W. O., Losordo, T. M., Fitzsimmons, K., and Hanley, F. (2002). Tilapia production systems in the Americas: technological advances, trends, and challenges. *Reviews in fisheries science*, *10*(3-4), 465-498.

Watson, C. A., and Shireman, J. V. (1996). Production of ornamental aquarium fish. University of Florida Cooperative Extension Service, Institute of Food and Agriculture Sciences, EDIS.

Weaver, D. E. (2006). Design and operations of fine media fluidized bed biofilters for meeting oligotrophic water requirements. *Aquacultural Engineering*, *34*(3), 303-310.

Wells, W. J. and Wendorff, B. (2004). Two-Stage, Low-Rate Anaerobic Treatment of Carbohydrate Wastewater from Two Food Processing Plants: Making the System Work. In *Proceedings of the Water Environment Federation*, *2004*(6). 62-84.

Westerfield, M. (2000). *The zebrafish book: a guide for the laboratory use of zebrafish (Danio rerio)*. University of Oregon Press.

Wickett, W. P. (1954). The oxygen supply to salmon eggs in spawning beds. *Journal of the Fisheries Board of Canada*, *11*(6), 933-953.Wimberly, D. M. (1990). *Development and evaluation of a low-density media biofiltration unit for use in recirculating finfish culture systems*. M.S. Thesis, Louisiana State University, Baton Rouge, Louisiana.

Wimberley, D. W., and Bello, R. (1992). Effects of foreign investment, exports, and economic growth on third world food consumption. Social Forces, 70(4), 895-921.

Worley, J. (2014). Greenhouses: heating, cooling and ventilation. University of Georgia Extension. *Bulletin 792*. 1-10.

Wright, P. A., and Fyhn, H. J. (2001). Ontogeny of nitrogen metabolism and excretion. *Fish physiology*, *20*, 149-200.

Yanong, R. P., Martinez, C., and Watson, C. A. (2010). Use of Ovaprim in ornamental fish aquaculture. Fisheries and Aquatic Sciences Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida.

Yokoyama, H., Ishihi, Y., Abo, K., and Takashi, T. (2010). Quantification of waste feed and fish feces using stable carbon and nitrogen isotopes. *Bulletin of Fisheries Research Agency (Japan)*, (31), 71-76.

Appendix A: ANOVA BOD, Protein, and nitrogen distribution

The results displayed in the box plots in Appendix A showed no significant difference in bala shark, blackfin tuna, cobia, catfish, and yellowfin tuna in terms of BOD_5 distribution. Each box plot shows an upper and lower range with a line across for the median. The average for each triplicate is the diamond at the center of the plot. The *y* axis shows the BOD_5 value in g/g. The graph in Appendix A shows that the bala shark, cobia, yellow and blackfin tuna lay in the same range across (between 0.6 and 0.65). Although catfish lay in the range 0.65-0.70, the SAS Tukey test shows no significant difference in all 4 species.

`

Results

The ANOVA Procedure

Class Level Information		
Class	Levels	Values
SPECIES	8	BALA SHARK BLACKFIN TUNA CATFISH COBIA SNAPPER SPECKLED TROUT TILAPIA YELLOWFIN TUNA

Number of Observations Read	24
Number of Observations Used	24

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One-Way Analysis of Variance

Results

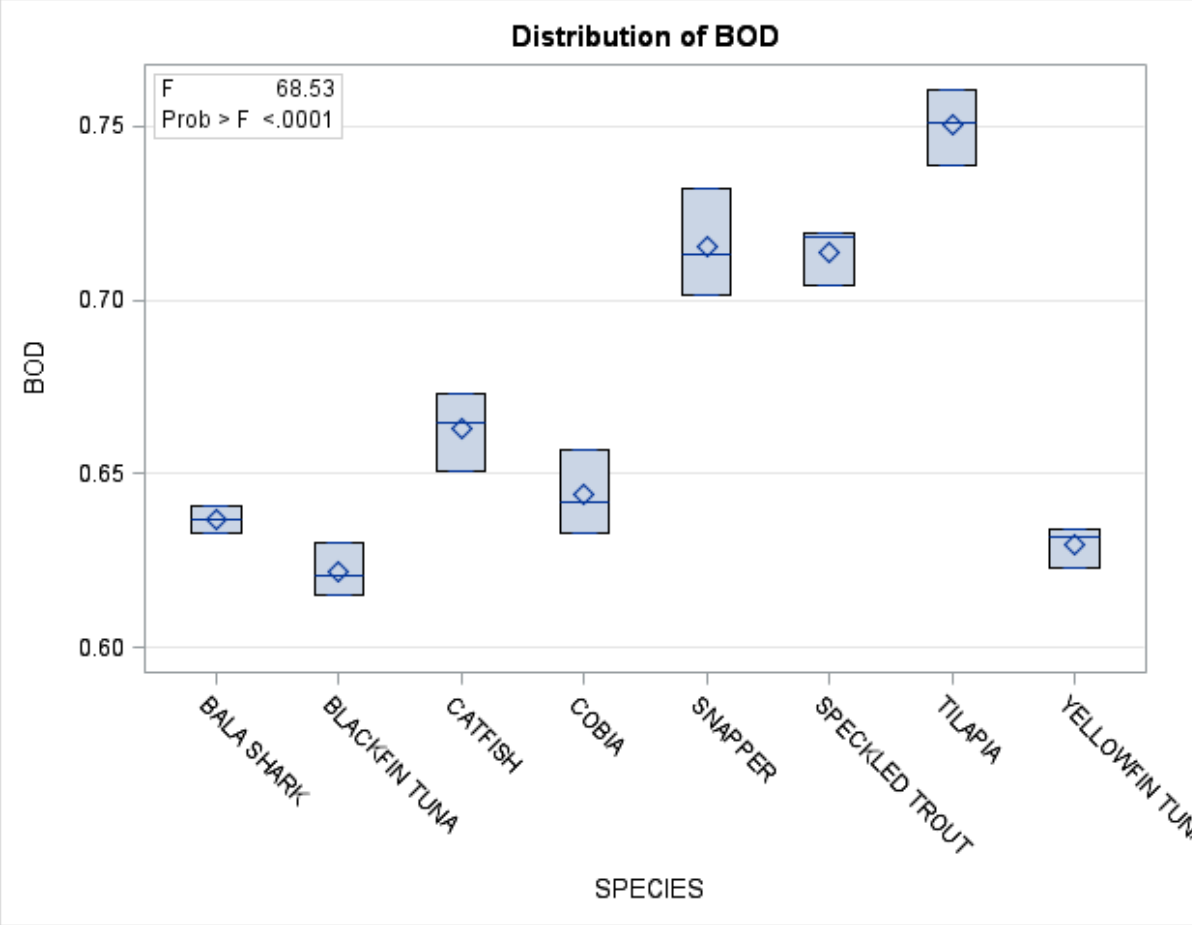
The ANOVA Procedure

Dependent Variable: BOD

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	0.04835064	0.00690723	68.53	<.0001
Error	16	0.00161263	0.00010079		
Corrected Total	23	0.04996327			

R-Square	Coeff Var	Root MSE	BOD Mean
0.967724	1.494255	0.010039	0.671867

Source	DF	Anova SS	Mean Square	F Value	Pr > F
SPECIES	7	0.04835064	0.00690723	68.53	<.0001



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One-Way Analysis of Variance

Results

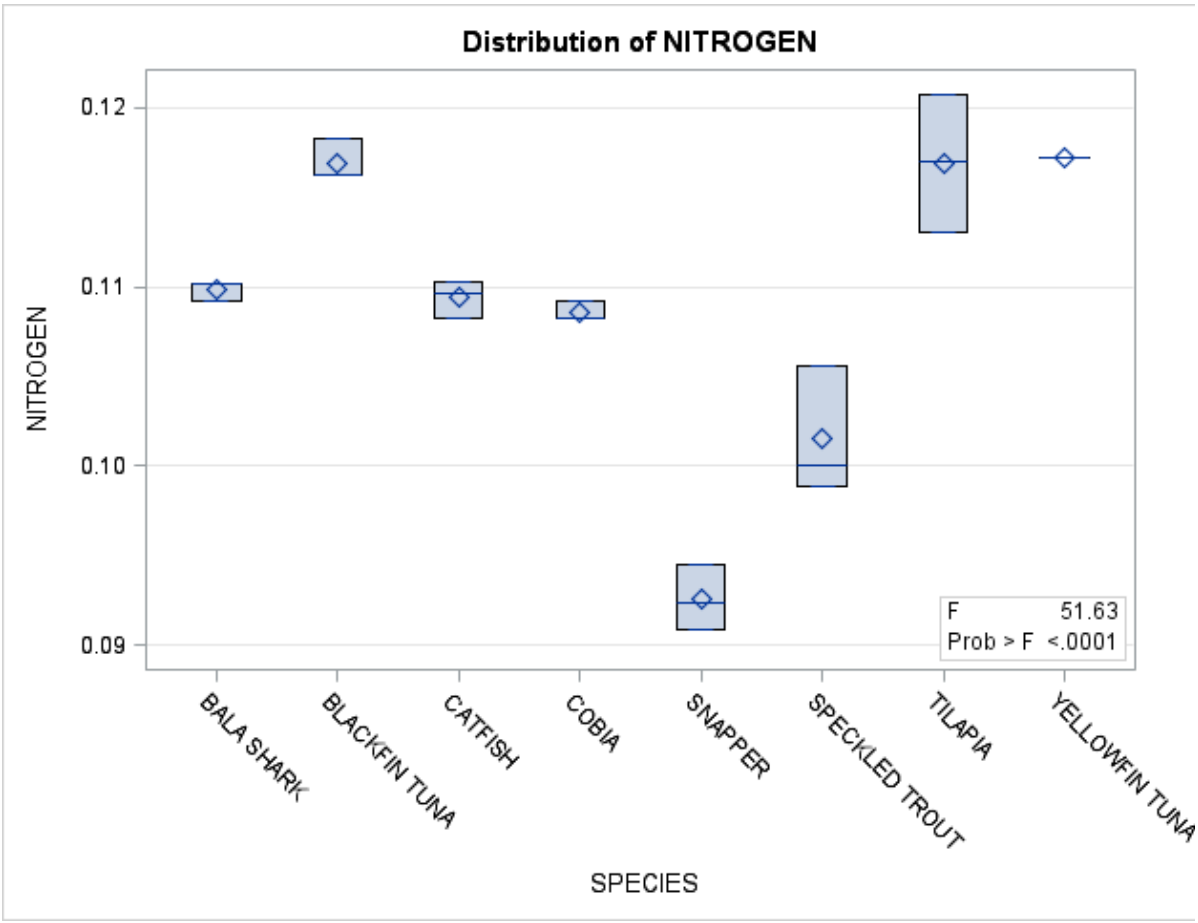
The ANOVA Procedure

Dependent Variable: NITROGEN

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	0.00155812	0.00022259	51.63	<.0001
Error	16	0.00006898	0.00000431		
Corrected Total	23	0.00162710			

R-Square	Coeff Var	Root MSE	NITROGEN Mean
0.957607	1.902627	0.002076	0.109129

Source	DF	Anova SS	Mean Square	F Value	Pr > F
SPECIES	7	0.00155812	0.00022259	51.63	<.0001



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One-Way Analysis of Variance

Results

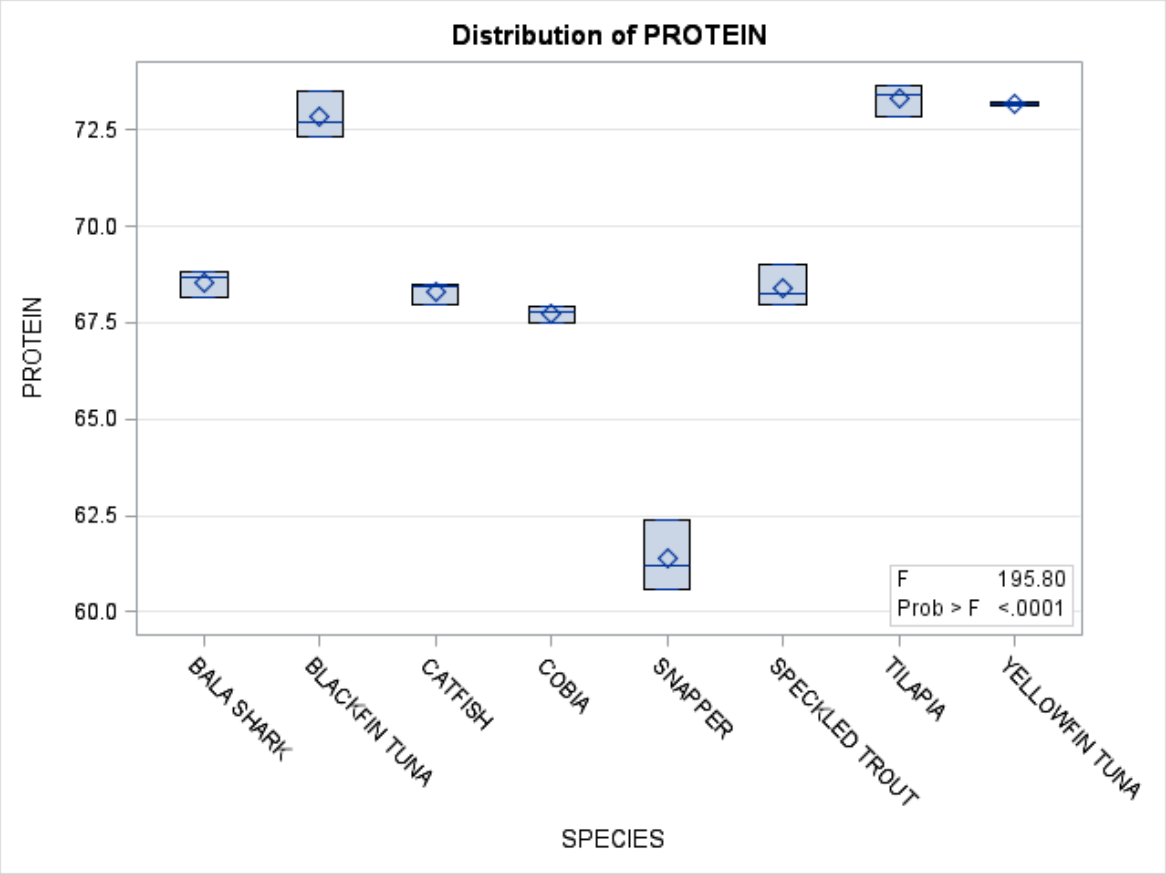
The ANOVA Procedure

Dependent Variable: PROTEIN

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	332.0218453	47.4316922	195.80	<.0001
Error	16	3.8759720	0.2422483		
Corrected Total	23	335.8978173			

R-Square	Coeff Var	Root MSE	PROTEIN Mean
0.988461	0.711082	0.492187	69.21667

Source	DF	Anova SS	Mean Square	F Value	Pr > F
SPECIES	7	332.0218453	47.4316922	195.80	<.0001



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One-Way Analysis of Variance

Results

The ANOVA Procedure

Levene's Test for Homogeneity of BOD Variance
ANOVA of Squared Deviations from Group Means

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
SPECIES	7	4.954E-8	7.077E-9	1.430	.2591
Error	16	7.895E-8	4.934E-9		

Levene's Test for Homogeneity of NITROGEN Variance
ANOVA of Squared Deviations from Group Means

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
SPECIES	7	3.45E-10	4.93E-11	2.900	.0367
Error	16	2.72E-10	1.7E-11		

Levene's Test for Homogeneity of PROTEIN Variance
ANOVA of Squared Deviations from Group Means

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
SPECIES	7	0.6820	0.0974	2.380	.0712
Error	16	0.6540	0.0409		

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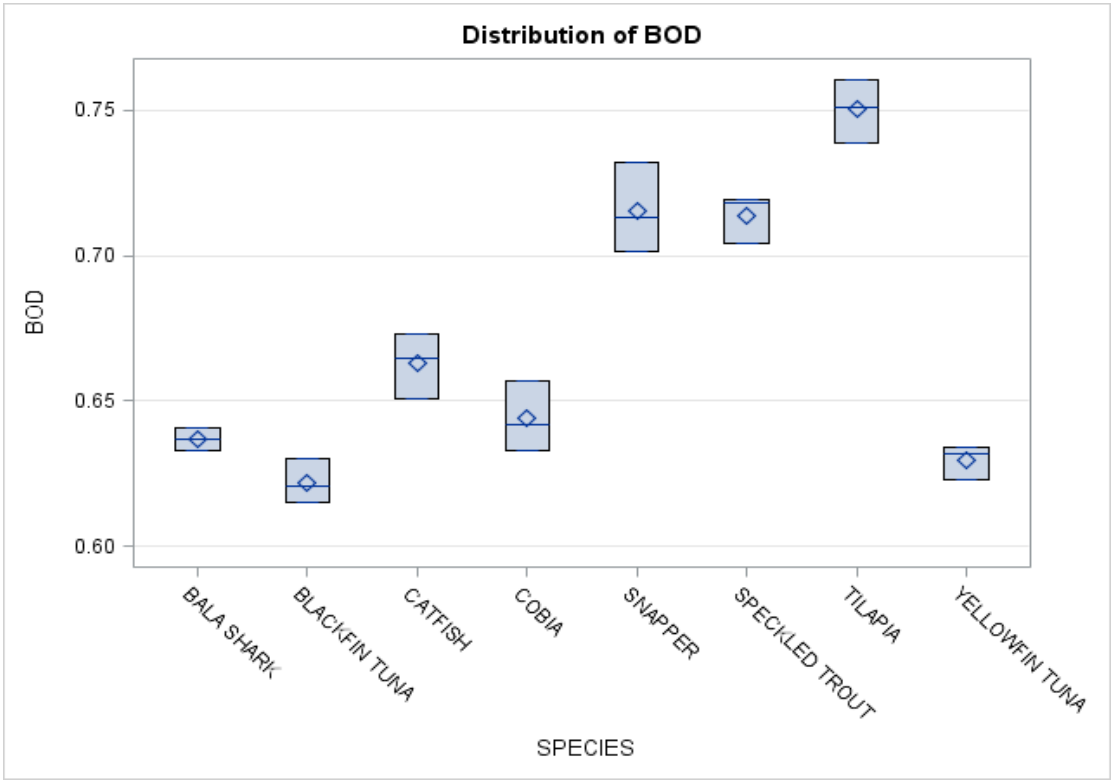
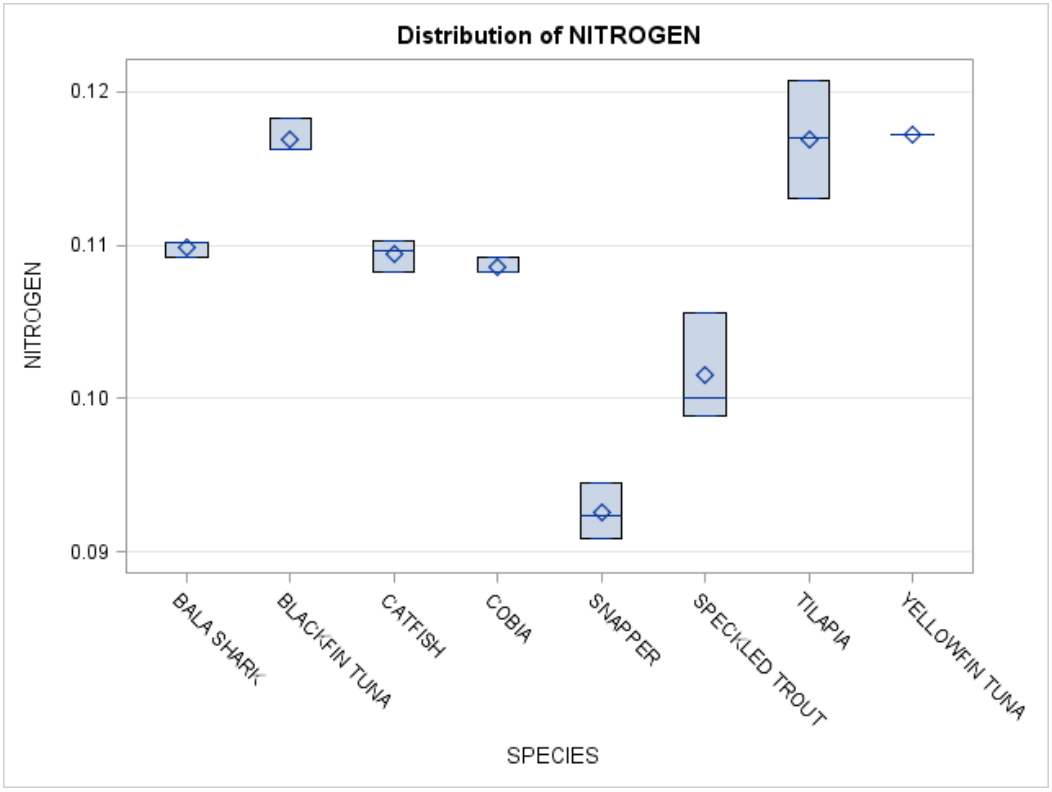
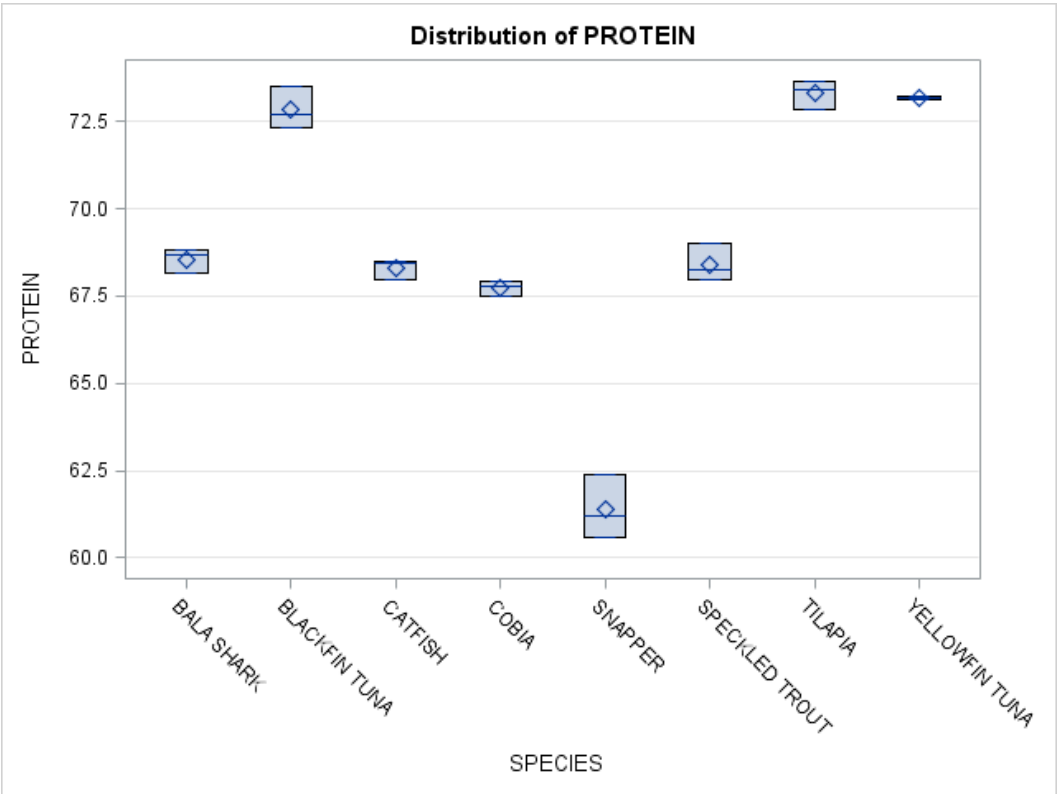
One-Way Analysis of Variance
Results

The ANOVA Procedure




Distribution of NITROGEN
NITROGEN
0.12
0.11
0.10
0.09
BALA SHARK
BLACKFIN TUNA
CATFISH
COBIA
SNAPPER
SPECKLED TROUT
TILAPIA
YELLOWFIN TUNA
SPECIES


Distribution of PROTEIN
PROTEIN
72.5
70.0
67.5
65.0
62.5
60.0
BALA SHARK
BLACKFIN TUNA
CATFISH
COBIA
SNAPPER
SPECKLED TROUT
TILAPIA
YELLOWFIN TUNA
SPECIES

Level of SPECIES	N	BOD		NITROGEN		PROTEIN	
		Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
BALA SHARK	3	0.6370000	0.0040000	0.1098860	0.0005785	68.549666	0.3622959
BLACKFIN TUNA	3	0.6220000	0.0075498	0.1169000	0.0011570	72.838333	0.6009179
CATFISH	3	0.6630000	0.0111355	0.1094250	0.0010454	68.320000	0.2868797
COBIA	3	0.6440000	0.0121243	0.1085500	0.0005785	67.741666	0.2244467
SNAPPER	3	0.7154000	0.0155396	0.0925948	0.0018502	61.400666	0.9162976
SPECKLED TROUT	3	0.7136666	0.0083865	0.1015126	0.0036159	68.403333	0.5463820
TILAPIA	3	0.7502000	0.0107782	0.1169334	0.0038586	73.310000	0.4160528
YELLOWFIN TUNA	3	0.6296666	0.0058594	0.1172340	0.0000000	73.169666	0.0414045

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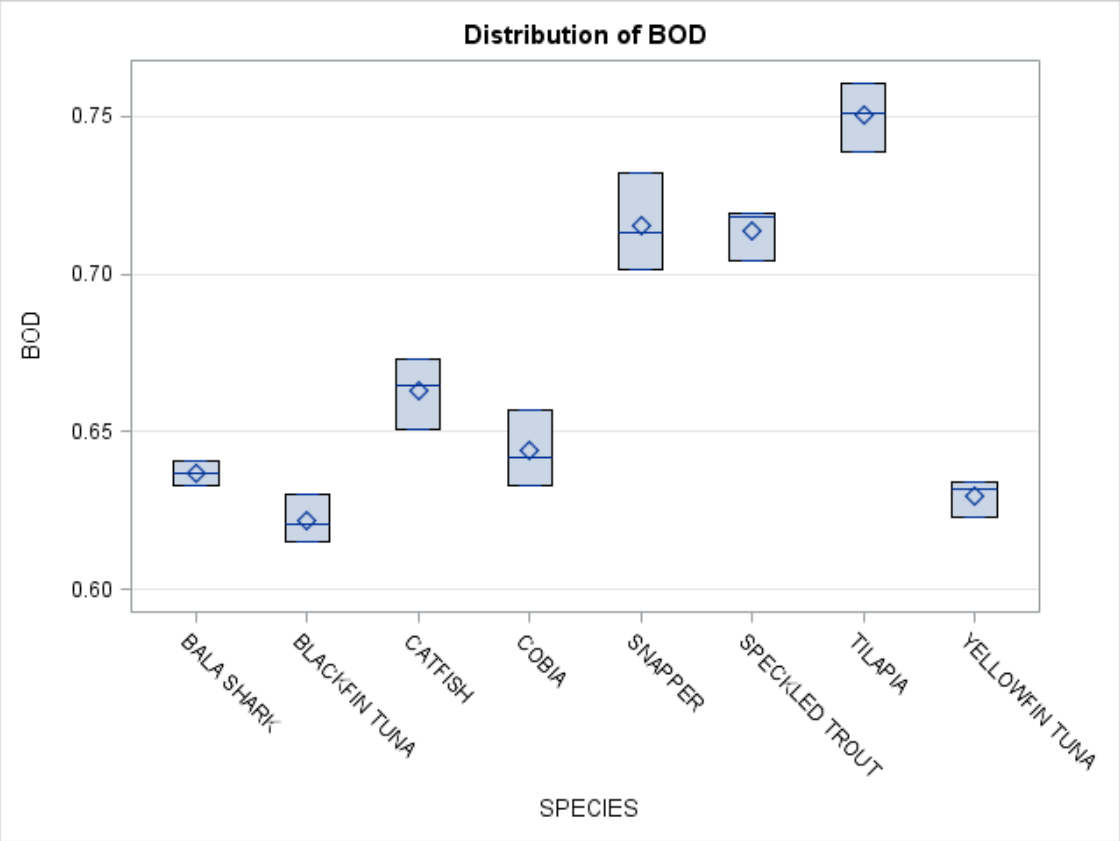
One-Way Analysis of Variance

Results

The ANOVA Procedure



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One-Way Analysis of Variance
Results

The ANOVA Procedure

Tukey's Studentized Range (HSD) Test for BOD

Note: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	16
Error Mean Square	0.000101
Critical Value of Studentized Range	4.89622
Minimum Significant Difference	0.0284

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	SPECIES
A	0.750200		3TILAPIA
B	0.715400		3SNAPPER
B			
B	0.713667		3SPECKLED TROUT
C	0.663000		3CATFISH
C			
D C	0.644000		3COBIA
D C			
D C	0.637000		3BALA SHARK
D			
D	0.629667		3YELLOWFIN TUNA
D			
D	0.622000		3BLACKFIN TUNA

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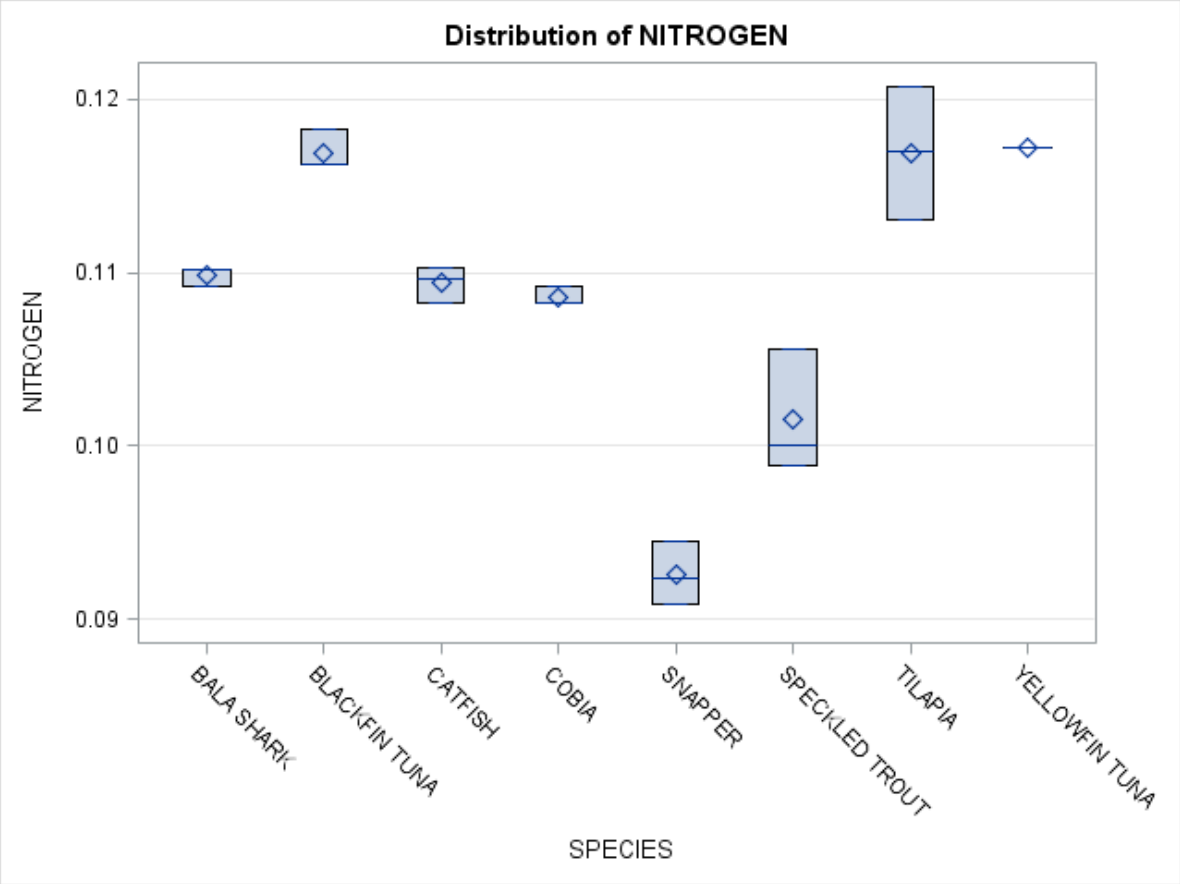
One-Way Analysis of Variance
Results

The ANOVA Procedure



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One-Way Analysis of Variance

Results

The ANOVA Procedure

Tukey's Studentized Range (HSD) Test for NITROGEN

Note: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	16
Error Mean Square	4.311E-6
Critical Value of Studentized Range	4.89622
Minimum Significant Difference	0.0059

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	SPECIES
A	0.117234	3	YELLOWFIN TUNA
A			
A	0.116933	3	TILAPIA
A			
A	0.116900	3	BLACKFIN TUNA
B	0.109886	3	BALA SHARK
B			
B	0.109425	3	CATFISH
B			
B	0.108550	3	COBIA
C	0.101513	3	SPECKLED TROUT
D	0.092595	3	SNAPPER

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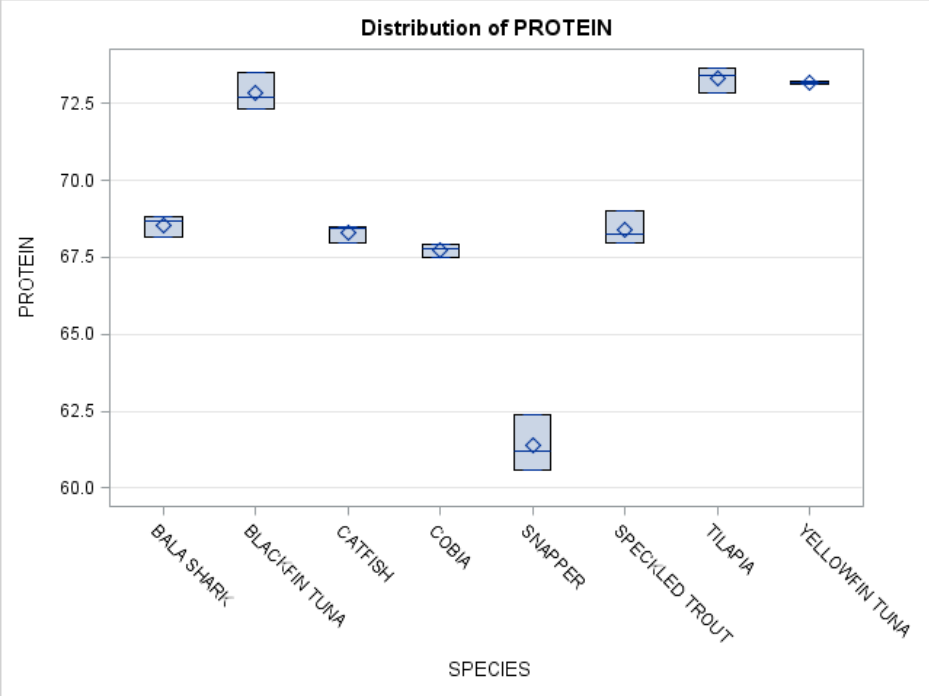
One-Way Analysis of Variance
Results

The ANOVA Procedure



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One-Way Analysis of Variance

Results

The ANOVA Procedure

Tukey's Studentized Range (HSD) Test for PROTEIN

Note: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	16
Error Mean Square	0.242248
Critical Value of Studentized Range	4.89622
Minimum Significant Difference	1.3913

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	SPECIES
A	73.3100	3	TILAPIA
A			
A	73.1697	3	YELLOWFIN TUNA
A			
A	72.8383	3	BLACKFIN TUNA
B	68.5497	3	BALA SHARK
B			
B	68.4033	3	SPECKLED TROUT
B			
B	68.3200	3	CATFISH
B			
B	67.7417	3	COBIA
C	61.4007	3	SNAPPER

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One-Way Analysis of Variance

Results

Means and Descriptive Statistics

SPECIES	Mean of BOD	Mean of NITROGEN	Mean of PROTEIN	Std. Dev. of BOD	Std. Dev. of NITROGEN	Std. Dev. of PROTEIN	Std. Error of BOD	Std. Error of NITROGEN	Std. Error of PROTEIN	Variance of BOD	Variance of NITROGEN	Variance of PROTEIN
	0.672	0.109	69.217	0.047	0.008	3.822	0.010	0.002	0.780	0.002	0.000	14.604
BALA SHARK	0.637	0.110	68.550	0.004	0.001	0.362	0.002	0.000	0.209	0.000	0.000	0.131
BLACKFIN TUNA	0.622	0.117	72.838	0.008	0.001	0.601	0.004	0.001	0.347	0.000	0.000	0.361
CATFISH	0.663	0.109	68.320	0.011	0.001	0.287	0.006	0.001	0.166	0.000	0.000	0.082
COBIA	0.644	0.109	67.742	0.012	0.001	0.224	0.007	0.000	0.130	0.000	0.000	0.050
SNAPPER	0.715	0.093	61.401	0.016	0.002	0.916	0.009	0.001	0.529	0.000	0.000	0.840
SPECKLED TROUT	0.714	0.102	68.403	0.008	0.004	0.546	0.005	0.002	0.315	0.000	0.000	0.299
TILAPIA	0.750	0.117	73.310	0.011	0.004	0.416	0.006	0.002	0.240	0.000	0.000	0.173
YELLOWFIN TUNA	0.630	0.117	73.170	0.006	0.000	0.041	0.003	0.000	0.024	0.000	0.000	0.002

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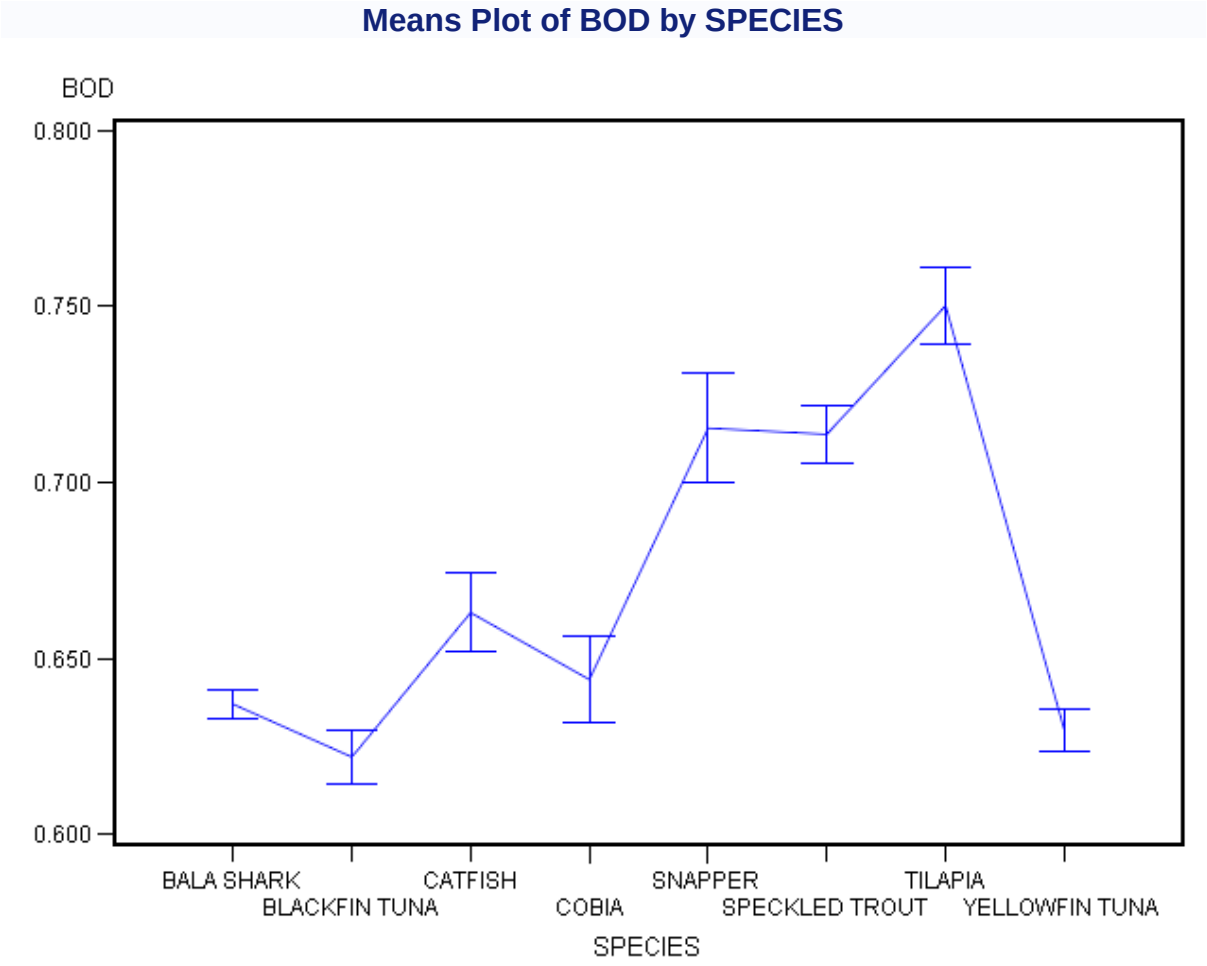
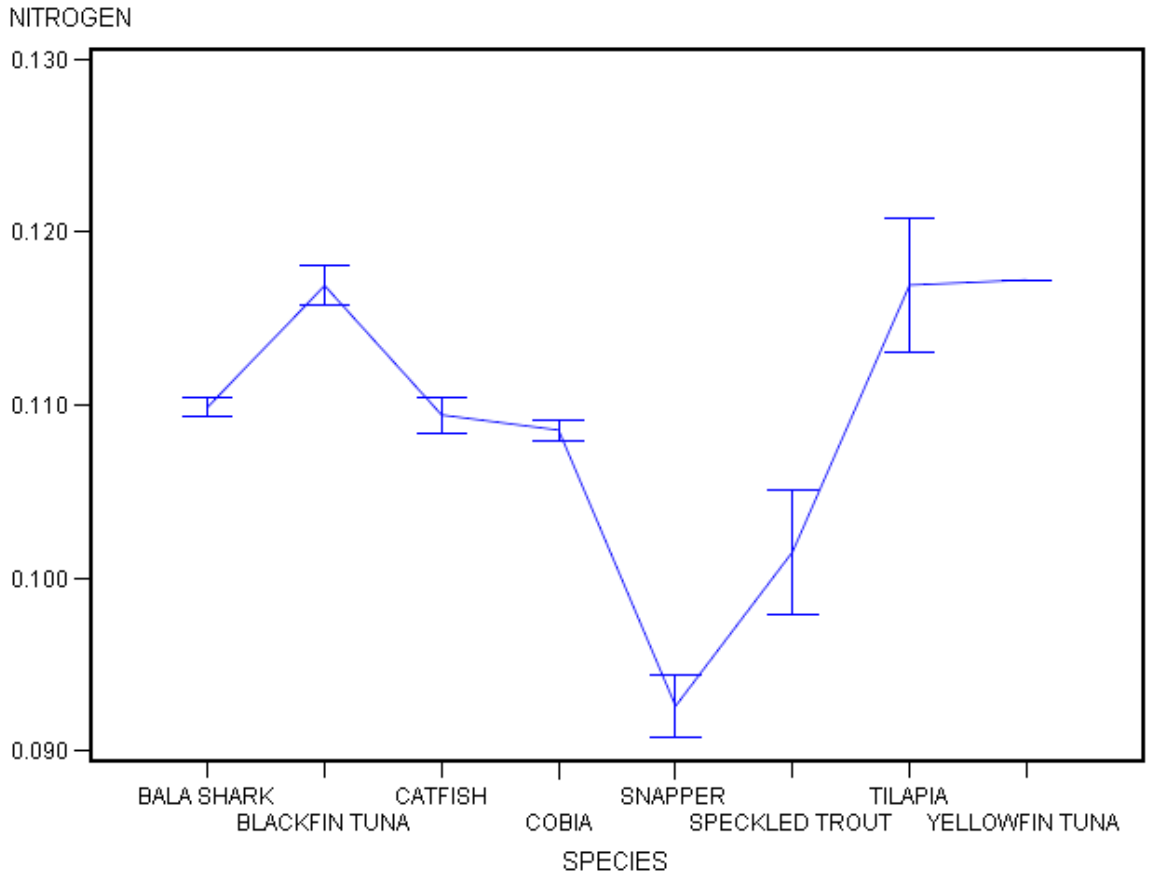
Appendix B: Mean plots of BOD, protein, and nitrogen loading



Means Plot of NITROGEN by SPECIES



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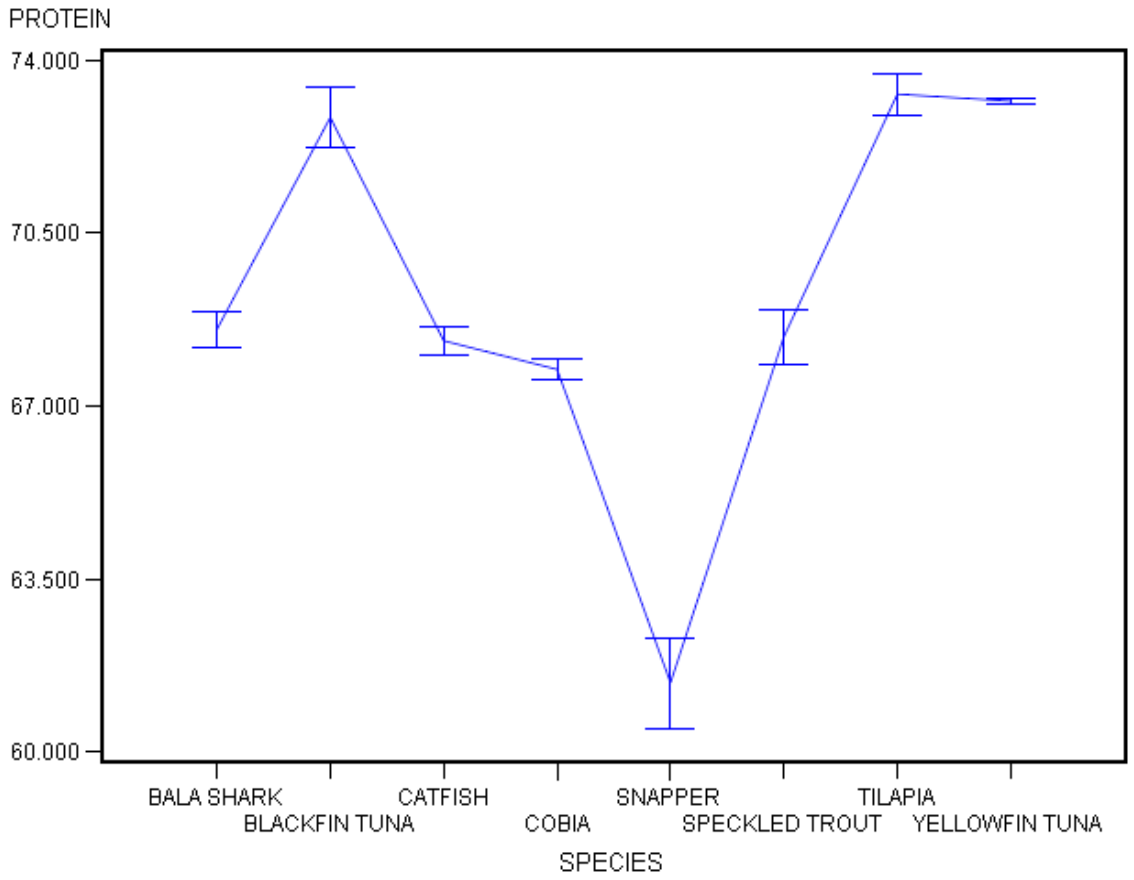
Means Plot of PROTEIN by SPECIES



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Appendix C: Fingerling and Growout Assumptions

C.1. Fingerling Assumptions

The fingerling tank volume allows us to calculate the maximum feed (F_{tmax}^{f}) allowed. F_{tmax}^{f}, equals the tank volume (V_t^f) divided by the recirculation rate (v_r^f), which is, 400 gal/lb. feed. The bead volume (V_b^f) is calculated by dividing F_{tmax}^{f} by the bead volume rate (v_b^f), that is, 0.75 ft³/lb./day. The bead filter size for each tank (F_s^f) is V_b^f divided byN_f^f, the number of bead filters per tank. The maximum production cost per tank per year (P_{max}^{f}) is F_{tmax}^{f} divided the feed ratio F/C multiplied by annual cycle A_c, 350 days for the annual cycle length. The maximum holding capacity H_{cmax}^{f} is F_{tmax}^{f} divided by the feed rate f_{bm}^{f}that is, 5 percent of body mass divided by the mortality rate M_r^f at 0.95. The density (δ^f) is given by H_{cmax}^{f} divided byV_t^f. The circulation (C_t^f) is F_{tmax}^{f} divided by the circulation rate q_r^f which is 10 gpm/lb. feed/day. Chemicals (mainly bicarbonate) help ensure appropriate alkalinity levels in the tank water. The amount of bi-carb $NaHCO_3$ per tank is obtained by multiplying $F_{tmax}^{f}$by the bi-carb daily dosage b_a^f and by A_c at 0.24 lb. bi-carb/lbs. feed. This means that chemical dosing is determined based on the amount of feeding administered, with a chemical/feeding ratio of 0.24 in lbs. The air needed for the airstone or aeration (A_s^f) is given by the airstone rate (g_a^f) at 4 scfh/lbs. feed-day multiplied by F_{tmax}^{f}. The flushing rate Q_f^f equals F_{tmax}^{f} multiplied by the water replacement rate q_f at 24.7 gal/lbs. feed/day. The tank recirculation rate Q_r^f is the circulation rate q_r^f multiplied byF_{tmax}^{f}. The number of fingerling N_f equal to the H_{cmax}^{f} multiplied by holding cycle 2.89 and the mortality rate M_r^f divided by average fingerling size f_s^f at 25 g or 0.06 lbs. The weight at harvest W_t is equal to number of fingerling N_f multiplied by harvest size of fingerling h_s at 50 g or 0.12 lbs. The feed

required F_r^f is equal to the weight at harvest W_t multiplied by the feed ratio F/C at 1.5 lbs. feed/lbs. fish. The average feed per day F_a is F_{tmax}^f multiplied by 0.5. The following tables summarize these parameters and their equations.

Table 23: Fingerling sizing constants per tank

Component sizing criteria	**Denotation**	**Value**	**Unit**
Airstone rate	g_a^f	4	scth/lbs. feed/day
Annual cycle	A_c^f	350	year
Average daily feed	F_a	12.5	lbs feed/day
Average fingerling size	f_s^f	25	g (or 0.06 lbs.)
Bead volume rate	v_b^f	0.75	ft³/lbs. fish/day
Bead filter sizes	b_s^f	35, 25, 50	cfm
Bi-carbonate	b_a^f	0.24	lbs. bicarb/lbs. feed/day
Circulation rate	q_r^f	10	gpm/lbs. feed/day
Feed rate efficiency	f_{eff}^f	0.75	%
Feed ratio	f_{bm}^f	5	% body mass
Feed ratio F/C	f_r^f	1.5	lbs. feed/lb. fish
Harvest size	h_s^f	50	g (or 0.12 lbs.)
Mortality rate	M_r^f	0.90	fish/year (5% m)
Number of bead filters per tank	N_f^f	2	filters
Number of tanks	N_t^f	4	tanks
Recirculation rate	v_r^f	400	gal/lbs. feed
Tank volume	V_t^f	12000	gal
Water replacement rate	q_f	24.7	gal/lbs. feed/day
Building totals			
Building volume	V_B^f	96000	gal
Building feed amount	F_B^f	100	lbs. feed/day
Building harvest	H_B^f	22200	lbs. fish/year
Bi-Carb	B_B^f	8400	lb. bi-carb

Table 24: Equations used to determine sizing (determined values) for fingerling tanks

Parameter	**Denotation**	**Unit**	**Equation**
Aeration	A_s^f	cfm/tank	$A_s^f = g_a^f \times F_{tmax}^f$
Bead filter size	F_s^f	lbs./ft³	$F_s^f = \frac{V_b^f}{N_f^f}$
Bead volume	V_b^f	ft³	$V_b^f = \frac{F_{tmax}^f}{V_b^f}$
Circulation	C_t^f	gpm./tank	$C_t^f = F_{tmax}^f * q_r^f$
Density	δ	lbs./gal	$\delta = \frac{H_{cmax}^f}{V_t}$
Feed requirement	F_r^f	lbs. feed/year	$F_r^f = W_h^f * f_r^f$
Flush rate	Q_f^f	gal/tank/day	$Q_f^f = F_{tmax}^f \times q_r^f$
Holding capacity max	H_{cmax}^f	lbs. fish/tank	$H_{cmax}^f = \frac{F_{tmax}^f}{f_{fr}^f M_r^f}$
Max tank production	P_{max}^f	lbs. fish/tank/year	$P_{max}^f = \frac{F_{tmax}^f}{v_b^f} \times A_c^f$
Maximum feed	F_{tmax}^f	lbs. feed/day/tank	$F_{tmax}^f = V_t^f{}_t / v_r^f$
NaHCO3 (bi-carbonate)	B_a^f	lbs. bicarb/tank/year	$B_a^f = F_{tmax}^f \times b_a^f \times A_c^f$
Number of fingerlings	N_f	fingerlings/tank/year	$N_f^f = H_{cmax}^f * M_r^f / f_s^f$
Recirculation rate	Q_r^f	gpm/tank	$Q_r^f = q_r^f \times F_{tmax}^f$
Weight at harvest	W_h^f	lbs. /year produce	$W_h^f = N_f^f * h_s^f$

C.2. Growout Assumptions

Based on the tank volume, we first calculate the maximum feed (F_{tmax}^g) allowed, that is, the tank volume V_t^g divided by the recirculation rate (v_r^g) which is 200 gal/lb. feed. The bead volume (V_b^g) is calculated by dividing F_{tmax}^g by the bead volume rate (v_b^g), that is, 1.5 ft³/lb./day. The bead filter

size for each tank (F_s^g) is V_b divided by the number of bead filters per tank. The maximum production cost per tank per year (P_{max}^g) is F_{tmax}^g divided by v_b^g multiplied by 350 days, that is, the annual cycle length otherwise referred to asA_c^g. The maximum holding capacity H_{cmax}^g is F_{tmax}^g divided by the feed ratio or feed rate (f_r^g), that is, 0.015 lb. feed/lb. fish/day. The density (δ^g) is given by H_{cmax}^g divided byV_t^g. The circulation (C_t^g) is F_{tmax}^g divided by the circulation rate q_r. The amount of bi-carb $NaHCO_3$ per tank is obtained by multiplying F_{tmax}^g by the bi-carb daily dosage b_a^g and byA_c^g. The air needed for the airstone (A_s^g) is given by the airstone rate (g_a^g) multiplied by F_{tmax}^g. The flush rate per day Q_f^g equals F_{tmax}^g multiplied by the water replacement rate q_r^g. The circulation rate Q_r^g is q_r^g multiplied by F_{tmax}^g . To calculate the number of growout N_g, we divide P_{max}^g by the product of the harvest weight (H_w) – the average weight of one fish at harvest time – and the feed rate efficiency (f_{eff}^g).

The following tables summarize these parameters and their equations.

Table 25: Growout tank sizing constants

Component sizing criteria	**Denotation**	**Value**	**Unit**
Air for airstone	g_a^g	4	scfh/lbs. feed/day
Annual cycle	A_c^g	350	days
Avg. fingerling size	f_s^g	25	g or (0.06 lbs.)
Beads	v_b^g	1.5	ft³/ lbs. feed/day
Beads filter sizes	b_s^g	35, 50, 75	cfm
Bi-carbonate	b_a^g	0.24	lbs. bicarb/lbs. feed
Circulation rate	q_r^g	6	gpm/lbs. feed/day
Feed rate efficiency	f_{eff}^g	0.75	%
Feed ratio	f_f^g	5	% body mass
Feed ratio F/C	f_r^g	1.5	lbs. feed/lb. fish/day
Harvest size	h_s^g	680	g or (1.5 lbs.)
Mortality rate	M_r^g	0.90	year (10% m)
Number of bead filters per tank	N_f^g	2	filters
Number of tank	N_t^g	4	tanks
Recirculation rate	v_r^g	200	gal/lbs. feed
Tank size	V_t^g	43000	gal
Water replacement	f_{ra}^g	8.2	gal/lbs. feed/day
Building totals			
Building volume	Vs	172000	gal
Building feed amount	Fs	860	lbs. feed/day
Building harvest	Hs	190630	lbs. fish/year
Bi-carbonate addition	Ba	72240	lb. bi-carb

Table 26: Equations used to determine sizing (determined values) for growout tanks

Parameter	**Denotation**	**Unit**	**Equation**
Aeration	A_s^g	cfm/tank	$A_s^g = g_a^g * F_{tmax}^g$
Bead filter size	F_s^g	lbs./ft³	$F_s^g = \frac{V_b^g}{N_f^g}$
Bead volume	V_b^g	ft³	$V_b^g = \frac{F_{tmax}^g}{V_b^g}$
Circulation	C_t^g	gpm/tank	$C_t^g = F_{tmax}^g * q_r^g$
Daily flush rate	Q_f^g	gal/tank/day	$Q_f^g = F_{tmax}^g * q_r^g$
Density	δ^g	lbs./gal	$\delta = \frac{H_{cmax}^g}{V_t}$
Feed requirement	F_r^g	lbs. feed/ year	$F_r^g = W_h^g * f_r^g$
Holding capacity max	H_{cmax}^g	lbs. fish/tank	$H_{cmax}^g = \frac{F_{tmax}^g}{f_{fr}^g * M_r^g}$
Max tank production	P_{max}^g	lbs. fish/tank/year	$P_{max}^g = \frac{F_{tmax}^g}{v_b^g} * A_c^g$
Maximum feed	F_{tmax}^g	lbs. feed/day/tank	$F_{tmax}^g = V_t^g{}_t / v_r^g$
NaHCO3 (bi-carbonate)	B_a^g	lbs. bicarb/tank/year	$B_a^g = F_{tmax}^g * b_a^g * A_c^g$
Number of fingerlings	N_{fing}^g	Fingerlings/tank/year.	$N_{fing} = H_{cmax}^g * M_r^g / f_s^g$
Number of growout fish	N_g	fish	$N_g = \frac{P_{max}^g}{H_w \times f_{eff}^g}$
Recirculation rate	Q_r^g	gpm/tank	$Q_r^g = q_r^g * F_{tmax}^g$
Tank volume	V_t^g	gal.	
Weight at harvest	W_h^g	lbs. produce/year	$W_h^g = N_{fing}^g * h_s^g$

Appendix D: Cost analysis equations

Equation 1: Determining the Number of Fingerling Tanks Needed

Fish is referred to as "fingerling" until age 12 weeks.

Production amount in lbs. = 1.25M lbs.

Initial fingerling weight for 1 gal. = 0.25 lb. $= \frac{454\text{ g}}{1\text{ lb.}} \times \frac{0.25\text{ lb.}}{1\text{ g}} = \frac{113.5\text{g}}{1\text{ gal.}}$

Weight of fingerling per tank (12 weeks) = $\frac{113.5\text{ g}}{1\text{ gal.}} \times 75000\text{ gal.} = \frac{70937.5\text{ g/tank}}{12\text{ weeks in fingerling tank}}$

1 year = 50 weeks

Annual production = 1.25M lbs. /year; Mortality rates 10%

Weekly production = $\frac{1.25\text{M lbs./year}}{50\text{ weeks}} = \frac{25000\text{ lbs.}}{1\text{ week}} \times \frac{1\text{ fingerling}}{1.5\text{ lb.}} \times 1.1 = \frac{18333\text{ fingerling}}{1\text{ week}}$

Number of tanks = $\frac{\text{weight of fingerlings per tank}}{\text{number of fingerlings per week}} = \frac{70937.5}{18333} = 3.87 \simeq 4$

Equation 2: Determining Pump Airlift HP requirements

$$\frac{Q_r \times \gamma \times \Delta h}{550} \times \frac{1}{\text{pump efficiency}} \times \frac{1}{\text{motor efficiency}}$$

Where

$Q_r = 0.448\ cfs$ [circulation requirement for one tank]

$\gamma = 62.4\ lbs./ft.^2$ [water density]

$\Delta h = 15\ psi = 35\ ft.$ [change is pressure] (Malone and Gudipati, 2005)

550 is the unit conversion constant

Equation 3: Horsepower per Tank for water flow

$$\frac{0.448 \times 62.4 \times 35}{550} \times \frac{1}{0.8} \times \frac{1}{0.8} = 2.78 \text{ hp}$$

Equation 4: Determining Operating Electrical Cost

The following conversion and electrical cost:

- 0.7457 kWh = 1 hp
- 1 kWh costs $0.10

Cost per tank per year C_t is thus computed using the following formula:

$$\frac{0.7457 \text{ kWh}}{1 \text{ hp}} \times 2.78 \text{ hp} \times \frac{\$0.10}{\text{kWh}} \times 24 \text{ hrs.} \times 360 \text{ days} = \$1815.99$$

Equation 5: Airlift Operation Cost per pound. Fish Harvested

$$E_c = \frac{C_t}{\text{total growout fish weight}}$$

Where

E_c is the electricity cost for airlift operation per lb. growout fish

C_t is the electricity cost for airlift operation per growout fish tank.

Equation 6: Filter Cost for the Facility

$$\text{filter cost for the facility} = \text{cost of 1 filter} \times \frac{\text{\# filters}}{\text{one tank}} \times \frac{\text{\# tanks}}{\text{one building}} \times \text{\# buildings}$$

$$22{,}000 \times 2 \times 4 \times 8 = 1408000$$

Equation 7: Feeding Cost for Fingerling per Tank for Each Cohort

$$\frac{f_{lb}}{1\ day} \times \frac{\mathrm{P}_{feed}}{f_{lb}} \times \phi_n days = C_{feed_{\phi_n}}$$

Equation 8: Total Fingerling Feeding Cost

$$C_{\phi_1} \times \phi_1 days + C_{\phi_2} \times \phi_2 days + C_{\phi_3} \times \phi_3 days = total\ fingerling\ feeding\ cost$$

Where

f_{lb} is the amount of feed in lbs., P_{feed} is the feed price in $, C_{feed} is the daily feed cost, and ϕ is the fingerling cohort.

Equation 9: Daily Fish Support per Cubic Foot of Beads

$$daily\ fish\ support\ per ft^3\ of\ beads = \frac{1.5\ lb. feed}{1\ ft^3.\ beads/day} \times 75\% \times \frac{1\ lb. fish}{1.5\ lb. feed} = \frac{0.75\ lb. fish}{1\ ft^3\ beads/day}$$

Equation 10: Daily Fish Support per Tank (43,000)

$$\text{daily fish support per tank} = \frac{0.75\text{ lb. fish}}{1\text{ft}^3\text{ beads/day}} \times \frac{75\text{ ft}^3\text{ beads}}{1\text{ filter}} \times \frac{2\text{ filters}}{1\text{ tank}} = \frac{112.5\text{ lbs. fish}}{1\text{ tank/day}}$$

Equation 11: Yearly Fish Support per Cubic Foot of Beads

$$\text{yearly fish support per ft}^3\text{ of beads} = \frac{0.75\text{ lb. fish}}{1\text{ ft}^3\text{ beads/day}} \times \frac{365\text{ days}}{1\text{ year}} = \frac{273.75\text{ lbs. fish}}{1\text{ ft}^3\text{/year}}$$

Equation 12: Yearly Fish Support per Tank

$$\text{yearly fish support per tank} = \frac{112.5\text{ lbs. fish}}{1\text{ tank/day}} \times \frac{365\text{ days}}{1\text{ year}} = \frac{41062.5\text{ lbs. fish}}{1\text{ tank/year}}$$

Appendix E: Optional cohort design criteria

E.1. Chemicals

The chemical cost is defined for each cohort in Equation 7 and then calculated in Equations 8 and 9, based on feeding amounts findings from Equations 6 and 5.

$$chemical\ cost\ per\ cohort = \frac{0.25\ lb.chemical}{1\ lb.feed} \times amount\ fed\ for\ cohort_n\ in\ lbs. \times \frac{chemical\ price}{1\ lb.chemical}$$

$$0.25 \times \frac{f_{lb}}{1\ day} \times \frac{\mathrm{P}_{chem}}{ch_{lb}} \times \phi_n days = C_{chem_{\phi_n}}$$

The first cohort tank of fingerlings is administered 0.3916mL per day (0.028 mL per lb. of fish), that is, a total of 35.244 mL over 90 days. Fingerlings are then administered 0.4624mL of chemicals daily, which means a total of 10.1728 mL for this second generation. From their arrival from the hatchery until their departure to the growout tanks, fingerlings are administered a total of 45.4168 mL of chemicals, leading to a cost of 45.4168 mL × $0.40 per cycle for one fingerling tank.

As for growout, the first cohort tank is administered 0.4624mL per day (1 lb. chemical per 50 lbs. of feed), that is, a total of 2.7744 mL over 6 days. The total cohort cost of chemicals at this level is $0.002 the fish are then administered 1.452 mL of chemicals daily for 4 weeks, which means a total of 40.656 mL for this second cohort. The chemicals cost for this level is $0.026. During the next 28 days, the total amount of chemicals increases to 57.904 mL, with a daily dose of 2.068 mL. The total cost associated with this phase is $0.037. The dose then increases to 2.4992 mL daily, that is, 69.9776 mL for these 4 weeks. The total cost associated with this phase is $0.044.

The last cohort before harvest is administered 2.596 mL daily, that is, 72.688 mL for these 28 days, resulting in a $0.046 cost.

E.2. Feeding

During the first 90 days (12.86 weeks or cohort 1), they are administered a daily dose of 19.58 lbs. of feeding, which means a total of 1,762.2 lbs. for this first cohort. The daily feeding cost and total feeding cost for cohort 1 are $7.24 and $652.01, respectively. Fingerlings are then on a daily diet of 23.12 lbs. of feeding, which means a total of 508.64 lbs. for this second fingerling cohort (cohort 2). The daily feeding cost and total feeding cost for this level are $8.55 and $188.20, respectively. From their arrival cohort 2 until their departure to the growout tanks, fingerlings are placed at cohort 3 where they are fed a total of 2270.84 lbs. of feeding, leading to a cost of $840.14 per cycle for one fingerling tank. Equation 5 summarizes the feeding cost for fingerling per tank for each cohort, and Equation 6 summarizes the total fingerling feeding cost.

During the first 6 days in the growout tank, the fish are still under cohort 3 as they are administered a daily dose of 23.12 lbs. of feeding, which means a total of 138.72 lbs. for this cohort. The daily feeding cost and total feeding cost for this cohort are $8.55 and $51.30, respectively. The fish are then on a daily diet of 72.6 lbs. of feeding for 28 days, which means a total of 2032.8 lbs. for cohort 4. Upon completion of this cohort, daily feed doses are increased to 103.4 lbs., for the next four weeks, leading to a total of 2895.2 lbs. for these 28 days (cohort 5). The corresponding daily and total costs for feeding are $38.26 and $1071.22, respectively. The following four weeks' generation, cohort 6, is administered 124.96 lbs. of feeding per day, which means that 3498.88 lbs. are fed at the end of these 28 days. Associated daily and total costs are $46.24 and $1,294.59, respectively. During the last set of four weeks, that is, cohort 7, the fish are fed 129.8 lbs. per day, that is, 3634.4 lbs. in total. The daily feeding cost and total feeding cost for this level are $48.03

and $1,344.73, respectively. From their arrival from the nursery until maturity for harvest, the fish are fed a total of 24,400 lbs. of feeding, leading to a cost of $9028.00 per growout cycle for one tank. Extensions of Equations 3 and 4 lead to the following calculations regarding growout feeding cost expressed in the following equation:

$$C_{\phi_3} \times \phi_3 days + C_{\phi_4} \times \phi_4 days + C_{\phi_5} \times \phi_5 days + C_{\phi_4} \times \phi_4 days + C_{\phi_5} \times \phi_5 days$$

$$= total\ growout\ feeding\ cost$$

Where

f_{lb} is the amount of feed in lbs.,

P is the feed price in $,

C is the daily feed cost, and

ϕ is the growout cohort.

Based on the design criteria, quantities calculated indicate that each tank provides an annual production of 13,811 fingerlings. To achieve this annual amount, feeding, bi-carbonate, and electricity requirements are 4,375 lbs, 2,100 lbs, and 6173 kWh per tank, respectively. Thus, production cost is $0.486 for each fingerling reaching growout stage.

Based on the design criteria, 1 ft³ beads supports 1.5 lb. of feed per day. The filters operate at 75% efficiency, meaning that in practice, 1 ft³ beads will support 75% of 1.5 lb. of feed, that is, 1.125 lb. The feeding ratio is 1.5 lb. of feed per lb. of fish, meaning that at 75% efficiency, one cubic foot of beads supports 0.75 lb. of fish. The beads available allow each tank to support 0.75 lb. fish daily, and 41,062.5 lbs. yearly. One filter remains functional for 30 years. This means that at the end of its life expectancy, a set of two filters will support $41062.5 \times 20 = 821250$ lbs. of fish.

The cost for operating fingerling tanks and caring for the fingerlings is largely made up of the feeding cost and the cost of chemicals for 112 days. Through the fingerling cycle, the fish are administered feeding at a ratio of 1.4 lb. of feeding per lb. of fish, feeding being priced at $0.37/lb. Thus, to complete a fingerling cycle, it therefore costs, in terms of feeding,

- $840.14 to feed 7500 fish
- $0.11 to feed one fish
- $840.14 to feed 1621.43 lbs. of fish (2270.84 lbs. of feeding divided by 1.4, 1.4 lb. to 1 lb. being the feed/fish weight ratio)
- $0.52 to feed 1 lb. of fish

The chemical compound is priced at $0.40 per lb. knowing that 0.24 lb. is required per lb. of feed. Cost values are obtained by multiplying feed amounts by 0.24 lb. × $0.40 = 0.096.

Appendix F: Annual Breakdown of Life Cycle Cost

Table 27: Life-cycle cost for one tank

Air TUBE	Backwash Blowers	Piping PVC + fittings	Tank	Box Truck	Stock	Feed	Chemical	Electricity	Labor	Transport	Heating	Greenhouse Purge Building	Metal Building Office & Storage	Greenhouse Growout	Maintenance	Total Cost
$ 17,200.00	$ 175.00	$ 2,000.00	$ 57,190.00	$ 20,000.00	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ 80,000.00	$ 24,500.00	$ 160,000.00	$ -	$ 458,508.90
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ -	$ -	$ 2,000.00	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 91,837.85
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ 17,200.00	$ 175.00	$ 2,000.00	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 111,068.90
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ -	$ -	$ 2,000.00	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 91,837.85
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ 17,200.00	$ 175.00	$ 2,000.00	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 111,068.90
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ -	$ -	$ 2,000.00	$ -	$ 20,000.00	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 111,837.85
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ -	$ -	$ -	$ -	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ -	$ -	$ -	$ 5,000.00	$ 89,837.85
$ 17,200.00	$ 175.00	$ 2,000.00	$ 57,190.00	$ -	$ 6,102.14	$ 20,881.88	$ 7,224.00	$ 3,254.83	$ 45,000.00	$ 375.00	$ 2,000.00	$ 80,000.00	$ 24,500.00	$ 160,000.00	$ 5,000.00	$ 443,508.90
$ 68,800.00	**$ 700.00**	**$ 14,000.00**	**$ 114,380.00**	**$ 40,000.00**	**$ 189,166.47**	**$ 647,338.13**	**$ 223,944.00**	**$ 100,899.63**	**$ 1,395,000.00**	**$ 11,625.00**	**$ 62,000.00**	**$ 160,000.00**	**$ 49,000.00**	**$ 320,000.00**	**$ 150,000.00**	**$ 3,575,777.44**

Appendix G: Greenhouse Heating Requirements

Heat requirement calculations are based on heat loss data that helps predict heating loads. Jones (2010) provided a heat loss equation by conduction:

$Q = U\ A\ (T_i - T_o)$

Where:

Q = heat transfer rate in BTU/hr.

U = heat transfer coefficient in BTU/hr.-ft^2 °F (1/R value)

A = surface area in ft^2

$T_i - T_o$ = air temperature difference between inside and outside in °F.

"U" values are sometimes substitutes for "R" values (resistance to heat flow), but Jones (2010) noted that the relation between "U" and "R" was: U = 1/R.

Jones (2010) also provided a complementary editable Excel spreadsheet that we edited by entering input from our proposed facility's buildings' data. The edited spreadsheet is presented in the following table:

DATA COLLECTED	ABR.		UNIT	
DIMENSION DATA				
GREENHOUSE ROOF SURFACE AREA	SR	100000		
GREENHOUSE WALL SURFACE AREA	SW	15000		
ENERGY CONSUMPTION DATA				
ANAUAL BOILER ENERGY CONSUMPTION	ECB	5000	/MMBTU	
INCREMENTAL ENERGY DATA				
ANAUAL BOILER FUEL COST	ICN	$15.00	/MMBTU	
ASSUMPTIONS				
EFFICIENCIES				
BOILER EFFICIENCY	NB	75	%	
ENVIRONMENTAL CONDITIONS				
HEATING DEGREE DAYS	HD	7500	F-DAYS/YR.	
MATERIAL PROPERTIES				
FIBER REINFORCED PLASTIC R-VALUE	RC1	0.83		
DOUBLE LAYER POLYETHYLENE R-VALUE	RC2	1.5		
CORRUGATED POLYETHYLENE R-VALUE	RP	2.3		
INTERNAL FILM RESISTANCE R-VALUE	R1V	0.68		
INTERNAL FILM RESISTANCE R-VALUE	R1S	0.62		
EXTERNAL FILM RESISTANCE R-VALUE	RE	0.31		
CONVERSION FACTORS				
ENERGY CONVERSION FACTOR	CF1	1,000,000		
TIME CONVERSION FACTOR	CF2	24	HRS/DAY	
R-VALUE DEVELOPMENT				
CURENT ROOF R-VALUE	RCR	2.43		**EQ. 1**
PROPOSED ROOF R-VALUE	RPR	2.43		**EQ. 2**
CURENT WALL R-VALUE	RCW	1.82		**EQ. 3**
PROPOSED ROOF R-VALUE	RPW	3.29		**EQ. 4**

Energy Savings Summary				
Current Annual Heat Loss	QLC	8890.9	MMBtu	Eq. 5
Annual Solar Heat Grain	QSG	3890.9	MMBtu	Eq. 6
Proposed Annual Heat Loss	QLP	8228.1	MMBtu	Eq. 7
Annual Energy Saving	ES	883.8	MMBtu	Eq. 8
Implementation Costs Summary				
Material cost				
Insulation Cost	CI	$1.81	/ft^2	Rf. 5
Material Cost	CM	$27,150.00		Eq. 9
Labor Costs				
Labor Rate	LR	$50.00	/hr	Rf. 5
Labor Hours	LH	0.0025	hr/ft^2	Rf. 5
Labor Cost	CL	$ 1,875.00		Eq. 10
Economic Results				
Cost Savings	CS	$ 13,256.96	/yr	Eq. 11
Implementation Costs	IC	$ 29,025.00		Eq. 12
Payback	PB		yrs	
Information For Narrative				
Energy (MMBtu)		883.8	MMBtu	
Energy (therms)		8838.0	MMBtu	
Cost Saving		$ 13,256.96		
Implementation Cost		$ 29,025.00		

Equations

Eq. 1) Current Roof R-Value (R_{CR})

$$R_{IS} + R_{C2} + R_E$$

Eq. 2) Proposed Roof R-Value (R_{PR})

$$R_{IS} + R_{C2} + R_E$$

Eq. 3) Current Wall R-Value (R_{CW})

$$R_{IV} + R_{C1} + R_E$$

Eq. 4) Proposed Wall R-Value (R_{PW})

$$R_{IV} + R_P + R_E$$

References

Rf. 1) This is the average boiler efficiency that we observed during our site visit. However, we recommended that you have your boiler(s) tuned, which would increase the efficiency. If this action is taken, it will result in a slightly lower cost savings for this recommendation.

Rf. 2) Heating degree days from www.degreedays.net

Rf. 3) Current wall insulation R-Value from http://attra.ncat.org

Rf. 4) Current roof insulation R-Value from http://attra.ncat.org

Rf. 5) Proposed wall insulation R-Value from http://solexx.com/

Rf. 6) ASHRAE Handbook of Fundamentals 1997

Equations

Eq. 5) Current Heat Loss (Q_{LC})

$$\frac{\left(\frac{1}{R_{CR}}\right) \times H_D \times S_R \times CF_2}{CF_1} + \frac{\left(\frac{1}{R_{CW}}\right) \times H_D \times S_W \times CF_2}{CF_1}$$

Eq. 6) Solar Heat Gain (Q_{SG})

$$Q_{LC} - EC_B$$

Eq. 7) Proposed Heat Loss (Q_{LP})

$$\frac{\left(\frac{1}{R_{PR}}\right) \times H_D \times S_R \times CF_2}{CF_1} + \frac{\left(\frac{1}{R_{PW}}\right) \times H_D \times S_W \times CF_2}{CF_1}$$

Eq. 8) Energy Savings (ES)

$$\frac{Q_{LC} - Q_{LP}}{\eta_B}$$

Eq. 9) Material Costs (C_M)

$$S_W \times C_I$$

Eq. 10) Labor Costs (C_L)

$$S_W \times L_R \times L_H$$

Eq. 11) Cost Savings (CS)

$$ES \times IC_N$$

Eq. 12) Implementation Costs (IC)

$$C_M + C_L$$

The above equations from Oregon State University Energy Efficiency Reference (2014) show the application of the heat requirement calculations in a sample automatic, computer-generated professional report.

Appendix H: Sensitivity Analysis Formulae

Present Worth

P= F $\frac{1}{(1+i)^N}$ Hence P=F (P/F, ì%, N)

Annual Worth

$A = P\left[\frac{i(1+i)^N}{(1+i)^N-1}\right]$ Hence A=P (A/P, ì%, N)

Future Worth

F=$P(1+i)^N$ Hence F=P (F/P, ì%, N)

Vita

Marlon Alberetos Greensword was born in 1979 in Spanish Town, Jamaica. He pursued his elementary education in Kitson Town All-Age School, and his secondary education at St. Catherine High School and St. Jago High School in Jamaica, where he received his high-school diploma. In 1998, he obtained a track-and-field scholarship to Gardner Webb University in Boiling Springs, North Carolina, where he majored in education. A year and a half later, he transferred to Louisiana State University, where he pursued his athletic activities while majoring in general studies. He obtained a Bachelor of Arts degree in general studies with concentrations in history, economics, and mechanical engineering in spring 2005. He then pursued another bachelor's degree in industrial engineering at Louisiana State University, which he received in fall 2007, followed by a Master of Science in the same department in summer 2010. He is now a Ph.D. candidate at the department of Civil and Environmental Engineering at Louisiana State University.